DIW Berlin

German Institute
for Economic Research

Discussion Papers

512

Georg Zachmann

Convergence of Electricity Wholesale Prices in Europe?

A Kalman Filter Approach

Berlin, September 2005

IMPRESSUM

DIW Berlin
Deutsches Institut für Wirtschaftsforschung
Königin-Luise-Str. 5
14195 Berlin
Tel. +49 (30) 897 89-0
Fax +49 (30) 897 89-200
www.diw.de

ISSN print edition 1433-0210
ISSN electronic edition 1619-4535

DIW Berlin

Discussion Papers 512

Georg Zachmann

Convergence of Electricity Wholesale Prices in Europe? A Kalman Filter Approach

Berlin, September 2005

Convergence of Electricity Wholesale Prices in Europe? - A Kalman Filter Approach - [*]

Georg Zachmann[†]

September 15, 2005

Abstract

This study tests the hypothesis that the ongoing restructuring process in the European electricity sector, as well as market participants' adaptation to the new legal framework, have caused electricity wholesale day-ahead prices to converge towards arbitrage freeness. Using hourly cross-border capacity auction results at the Dutch-German and at the Danish-German border for the years 2002 to 2004, and the respective spot prices, we estimate a time-varying coefficient model based on the law of one price (LOP). The results of these estimations are used to calculate the speed of convergence towards the LOP. While the German - Dutch prices and the German - West Danish prices are clearly developing towards arbitrage freeness, the German and East Danish prices do not exhibit significant convergence.

Keywords: Electricity Prices, European Integration, Time Series Analysis

JEL classification: L94, C5, G1

---

[*] The study has been conducted in the framework of the SESSA Work Package 5. The author would like to thank Christian von Hirschhausen, Franziska Holz and Boriss Siliverstovs for their many helpful comments and discussions regarding this work. All remaining errors are the author's sole responsibility.

[†] DIW Berlin, gzachmann@diw.de

Contents

List of Tables

1 Introduction

Electricity markets throughout Europe have undergone significant changes in recent years. These developments have mainly been due to European economic policies that target the creation of a single sustainable European market for goods and services and thus for electricity, as well. The focus of these policies is on stimulating competition and reaping gains from international cooperation through such means as reserve sharing and combining different national consumption and production patterns. A common electricity market is expected to increase welfare by ensuring security of supply and improving allocation through more cost-reflective prices. Two important directives, one regulation and a variety of decisions have been issued by the European Union obliging all old and new EU member states to make substantial reform efforts to prepare the path for the development of a single European electricity market. These various measures require that markets be opened (e.g. Directive 2003/54/EC), obstacles to cross-border trade be reduced (Regulation 1228/2003), and non-discriminatory third-party access be guaranteed (e.g. Directive 2003/54/EC). The implementation of these obligations into national law has differed significantly among countries, and therefore a variety of reports benchmarking national electricity sector reforms have been issued (e.g. EC (2005), OXERA (2004), EBRD (2004)). They reveal that although substantial progress has been made in recent years some, national markets still face major obstacles to market entry and electricity trade.

Given structural changes that have taken place in the national electricity sectors in recent years, this paper asks whether market outcomes indicate an improved competitive situation in Europe. A strong indicator for the success of market reforms is the interaction of price signals across countries. Similar electricity prices throughout Europe[2] would be evidence of a single European electricity market. The studies of Bower (2002), Boisseleau (2004) as well as Armstrong and Galli (2005) compare electricity day-ahead wholesale prices at various power exchanges in Europe. Bower (2002) applies correlation and cointegration analysis to prices from the Nordic Countries, Germany, Spain, England and Wales as well as the Netherlands in 2001.[3] He concludes that

---

[2] When corrected for transmission costs and congestion fees.

[3] Boisseleau points out that the cointegration approach used in Bower's analysis is inappropriate because the original price series contained no unit root. In addition, Bower's use of unweighted daily average data is a flaw, given the strong differences between peak

some integration of European markets was already in evidence in 2001, especially between the Netherlands and its neighbors and within the NordPool area. The relevant chapter in Boisseleau (2004) focuses on regression and correlation analysis. He finds that the level of integration of European markets is very low, and that, except for the NordPool, European prices contain no unit root. Both, Bower (2002) and Boisseleau (2004) describe the respective status quo of electricity market integration. By way of contrast, Armstrong and Galli (2005) analyze the European price developments over time. They study the evolution of price differentials between France, Germany, the Netherlands and Spain in the years 2002 to 2004 and conclude that European electricity markets converged during this period. Although this study is a step forward, since it was the first to analyze the process of price convergence in Europe it contains several flaws. *First*, the reasoning is based on the comparison of only three yearly averages of price differentials. Given the large number of data points (the three years amount to 26,304 hours) this approach is relatively undifferentiated. *Second*, no statistical tests were performed on the significance of the dissimilarity of the yearly average price differentials. And *third*, the study excludes available relevant information - such as the results of the explicit cross-border capacity auctions between the Netherlands and Germany.

In this paper, we propose a different approach. We investigate the success of European electricity sector reforms by analyzing the development of wholesale prices over time. The hypothesis that prices converge is derived from both the potential instantaneous effects of the various reform steps on prices and the assumed indirect reaction due to market players adapting to the new framework. The hypothesis of price convergence will be tested by applying a time-varying coefficient model to day-ahead electricity prices in Denmark, Germany and the Netherlands. This approach was chosen in order to monitor a continuous evolution over time. The countries considered were selected with respect to the availability of transmission capacity auction results, which allow us to incorporate cross-border transmission costs into the analysis.

In the next section, the electricity wholesale day-ahead price series for eight price zones in Europe are introduced, and their interaction is studied by means of static principal component analysis. Then the cross-border transmission auction results are presented and relevant arbitrage opportunities in

---

and off-peak price behavior on the electricity market.

international electricity trade are discussed. The third section describes a time-varying coefficient model and applies it in order to test whether prices at the Dutch-German and the Danish-German border converged during the years 2002 to 2004. Section four draws policy conclusions from the analysis.

2 Data

2.1 Wholesale spot prices

Workable wholesale markets are a cornerstone of the European way to building a common electricity market. Thus, most of the old and some of the new member states have established power exchanges in recent years. Usually "day-ahead" (spot) and "future" contracts are traded on these markets. The varying maturities of future contracts make it difficult to compare price developments among markets. By way of contrast, the number of products on spot markets is far lower. Usually only electricity for single hours of the following day as well as for different bands, like peak and off-peak periods, are traded. Since the definition of load periods varies across markets, and because single hour prices give a much more detailed impression of intraday developments the latter are used in this analysis. A further advantage of hourly spot prices is the reflection of the current market situation whereas many of the uncertainties found on future markets are absent.

This study uses data on three West European countries (France, Germany, Netherlands), two Central European new EU member states (Poland, Czech Republic) and three North European price areas (East Denmark, West Denmark, Sweden). Spot market volumes and abbreviations used for these markets are summarized in Table 1. Note that since the participation in the considered wholesale spot markets is voluntary, their liquidity only represents a relatively small fraction of domestic consumption. Especially the French, Polish and Czech day-ahead prices stand for only a minor market segment.

Despite all differences in structure, liquidity, products and market mechanisms, the power exchanges in France (Powernext), Germany (EEX), the Netherlands (APX) and Poland (PolPX) all exhibit similarly function "day-ahead" segments of their respective national markets. The Nordic countries (Denmark, Finland, Norway and Sweden) have a common power exchange called NordPool, which organizes the joint spot market Elspot. In order to incorporate congestion into the price formation mechanism, the Nordic re-

Table 1: Spot market volumes and abbreviations

Abbreviation - Power Exchange	Spot Market Volume in GWh 2004	Total Consumption in GWh 2004[4]
APX - Amsterdam Power Exchange	13,402	110,047
EEX - European Energy Exchange, Leipzig	59,414	513,015
DKE - East Danish NordPool price area		14,251
DKW - West Danish NordPool price area		21,244
SWE - Swedish NordPool price area		145,476
PNX - Powernext, Paris	14,179	475,966
PPX - Polish Power Exchange, Warsaw	1,590	130,275
OTE - Czech Market Operator	289	61,449

gion is split into different price areas, for which spot prices and congestion fees are calculated simultaneously. Finally, the Czech market operator OTE also organizes a day-ahead market. Although OTE is not a typical power exchange, it provides the only available data on hourly spot prices from this major electricity-exporting country.

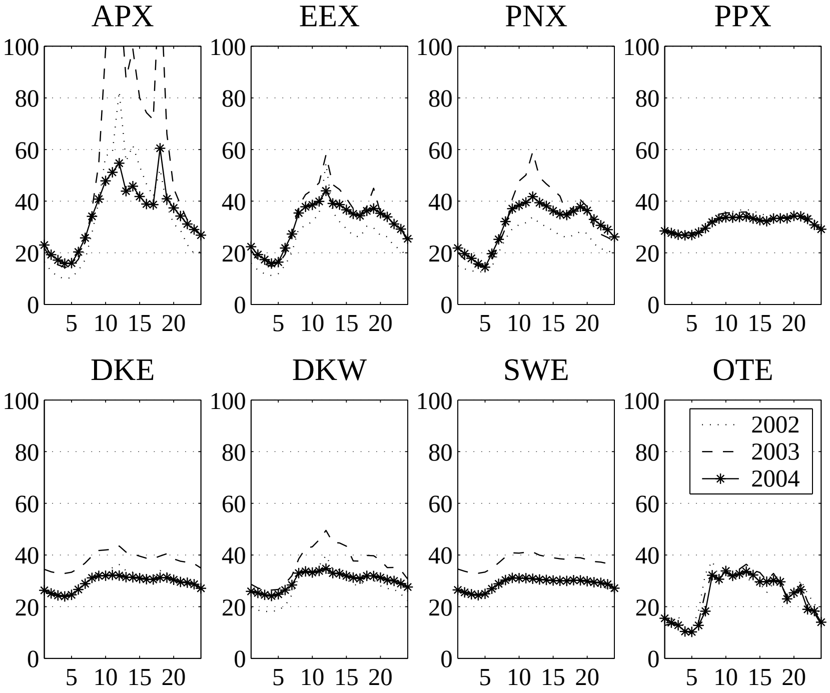
Figure 1 reveals one of the peculiarities of electricity prices - their strong seasonalities. In Amsterdam, for example, average power prices at the 12th hour (11am-12am) were around three times higher than average prices of the 4th hour (3am-4am) in 2004. These large differences over the course of the day are due to the non-storability of electricity. In addition to the daily patterns, weekly and yearly seasonalities also exist. Unless these price fluctuations are less severe in some of the power markets considered[5], they have to be coped with. Because daily, weekly and yearly seasonalities interact, national holidays differ across countries and seasonality effects themselves change over time it is very difficult to deseasonalize the data. Therefore we circumvent the seasonality problem by dividing all series into 24-sub series each of which represents one hour of the day. The weekly seasonalities have

---

[4] Source: Nordel and UCTE.

[5] The relatively modest daily seasonalities in Poland and Sweden have very different causes. The low price volatility in Poland can be linked to the low liquidity of the Polish market which signals inefficient pricing and the high number of combined heat and power plants that run no matter what the prices are. On the other side, the relatively flat Swedish and East-Danish price profiles are explained by the high share of hydropower in the region (Norway).

Figure 1: Yearly average wholesale electricity spot prices for each hour of the day



been removed mainly by excluding all Saturdays and Sundays from the sample.[6] Thus we obtain 192 series (8 x 24) consisting of 784 weekdays each. Finally the missing values in each series are replaced by the last observed value. The conversion into euros is done using the daily exchange rates provided by www.oanda.com.

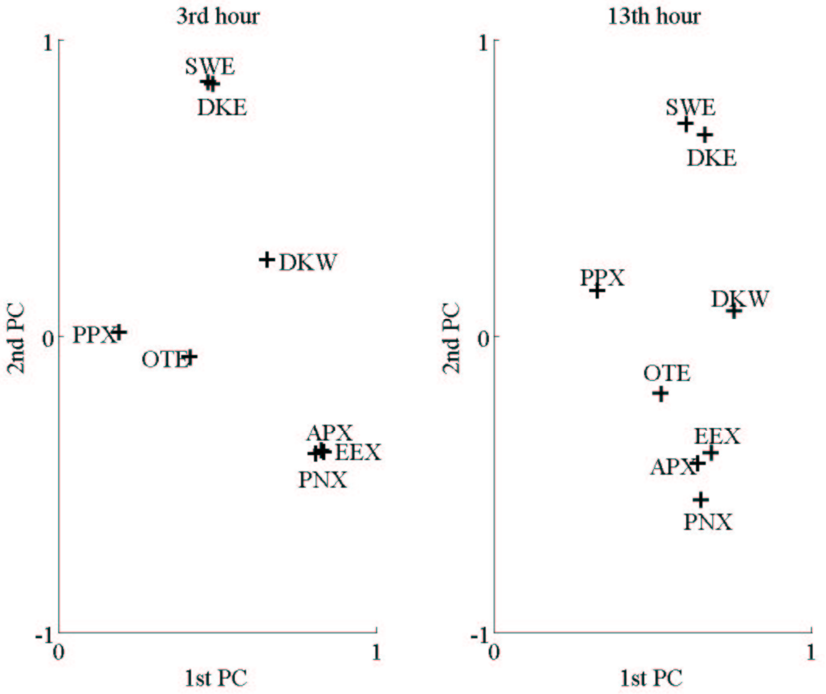
To assess the quality of the obtained data sets, two pretests have been performed. *First* we check the unit root hypothesis as the absence of a unit root is both a typical statistical feature of electricity prices and a prerequisite for many statistical methods.[7] The results of the ADF tests suggest that

---

[6] By modeling the Amsterdam, Leipzig and London spot prices with dummy variables for Saturdays and Sundays Huisman and Mahieu (2003) found that these dummies were significant and prices were always lower on Sunday. Since we are more concerned with decreasing the degrees of freedom than with using all available data, we decided to completely exclude weekends from the sample.

[7] Lucia and Schwartz (2001) as well as Worthington et al. (2005) concluded that the

Figure 2: Yearly average wholesale electricity spot prices for each hour of the day



the week-days electricity prices for the eight wholesale markets considered do not experience unit root behavior.[8] This absence of a unit root in electricity prices can be partly explained by the fact that in contrast to most other commodities, power is not economically storable and thus cannot easily be allocated between different periods. Therefore today's electricity prices are basically not the best guess for tomorrow's prices, which is what the unit root hypothesis suggests.

Second, a Principal Component Analysis (PCA) is performed to reveal

---

electricity spot prices they analyzed were stationary. Note however, that De Vany and Walls (1999) found a unit root in electricity spot prices of the Western US.

[8] Only for one hourly series of the Swedish prices the unit root hypothesis could not be rejected at the 99% significance level. At the 95% level the unit root hypothesis was rejected for all series considered. The detailed results are given in the appendix (Table 4). We used 5 lags and incorporated a constant in the estimation.

the interaction between the price series.[9] The underlying idea of PCA is to calculate the linear combinations of the original data matrix explaining most of the variance. Our data matrix consists of the week-day price series for the eight wholesale markets at a certain hour of the day. We calculate the first and second principal component (PC) for the normalized data, and compute the correlation between the PCs and the original data.[10] The results are summarized in the form of a scatter plot. As Figure 2 indicates, the eight wholesale markets can be roughly divided into three regional groups. The first group consists of the Dutch, German and French market. The second group contains the two Nordel transmission sub-zones East Denmark and Sweden. The third is made up of the two new EU member states, Poland and the Czech Republic. The only market that cannot be clearly attributed to either of these groups is the West Danish price area of the NordPool. At the same time, Figure 2 indicates that the West Danish price is located at the halfway point of a line connecting the Nordic and the West European markets, which algebraically represents its real function as link between those two regional markets. Together with the aforementioned clustering of strongly interconnected markets, this is evidence that at least some arbitrage between neighboring countries is taking place and thus that the data are likely to be appropriate for the following in-depth analysis.[11]

Although principal component analysis is able to provide evidence of dis-

---

[9] For the technical details of PCA see for example Jackson (1991).

[10] Detailed results can be found in the Appendix (Table 5).

[11] Note however, that some of the common regional developments can be explained by shared supply and demand conditions (especially weather) and that thus not all correlation is due only to arbitrage between countries. To assess the importance of this effect we analyzed the interactions of hourly spot volumes and prices. The hypothesis that the correlation of weather-driven demand and supply shocks in different regions is partly responsible for their correlated market outcomes implies that, assuming those uncertainties could not be included in the forward markets, traded volumes in the spot markets are correlated. When using an OLS-regression of detrended first differences of the weekdays spot volumes of the Nordic, Dutch and German markets, no significant relationship between their spot market volumes could be found (see Figure 8 in the Appendix). Furthermore, the same methodology was unable to show a clear link between the spot volumes and the spot prices in the Dutch, French and German markets (see Figure 9 in the Appendix). Only for the Nordic market was a significant relationship between spot prices and spot volumes to be found. Because no evidence was to be found for the hypothetical transmission process that links an unexpected regional weather event to higher spot market volumes in the region, ultimately leading to higher prices, the magnitude of this effect seems to be limited.

tinct regional price developments and thus of the existence of international arbitrage possibilities, it does not allow us to examine whether markets converge or diverge over time. Furthermore, a complete description of international electricity wholesale markets is only possible when incorporating the allocation mechanisms of cross-border transmission capacities into the analysis.

2.2 Cross border transmission auction results

In order to trade electricity between countries it must be transmittable. This is made possible by cross-border transmission lines. Due to the limited capacity of these lines, the right to use them in case of excess demand has to be allocated to the interested parties. These so-called congestion management methods vary significantly throughout Europe (for more details see ETSO (2004)). Applied methods range from first-come, first-serve approaches used by Belgium and France, to explicit auctions as used between Germany and the Netherlands and the implicit auctions used in the NordPool area. The advantages and disadvantages of these methods are discussed in ETSO (2004) and CONSENTEC (2004). Apart from allocation distortions, the non-auction-based congestion management methods also fail to provide data on the utilization of interconnection lines and the actual willingness to pay for the limited capacities.[12] On the other hand, the implicit auctions of the NordPool area fulfill the arbitrage freeness condition by construction. Therefore, only daily auction results for the Dutch-German and the Danish-German border are available for our analysis.

On the Danish-German border there are three adjacent transmission zones, one on the German (EON) and two on the Danish side (Eltra and Elkraft). Since the West Danish transmission network operated by Eltra is part of the West European UCTE-transmission system, and since the East Danish network (Elkraft) operates within the Nordel system, interconnection capacities between them are relatively low and thus prices differ significantly . Therefore, both Danish areas are incorporated into the analysis.

On the Dutch-German border, the auction is operated by TenneT, the

---

[12] It is worth noting that there are projects for the replacement of non-auction based methods by explicit auction between some of the countries considered. For example the transmission system operators (TSO) in Poland (PSE), the Czech Republic (CEPS) and Germany (Vattenfall ET) are planning a joint explicit daily auction of their interconnection capacities.

Figure 3: Cross-border transmission price differential (export price minus import price) in Euro/MWh 2002-2004

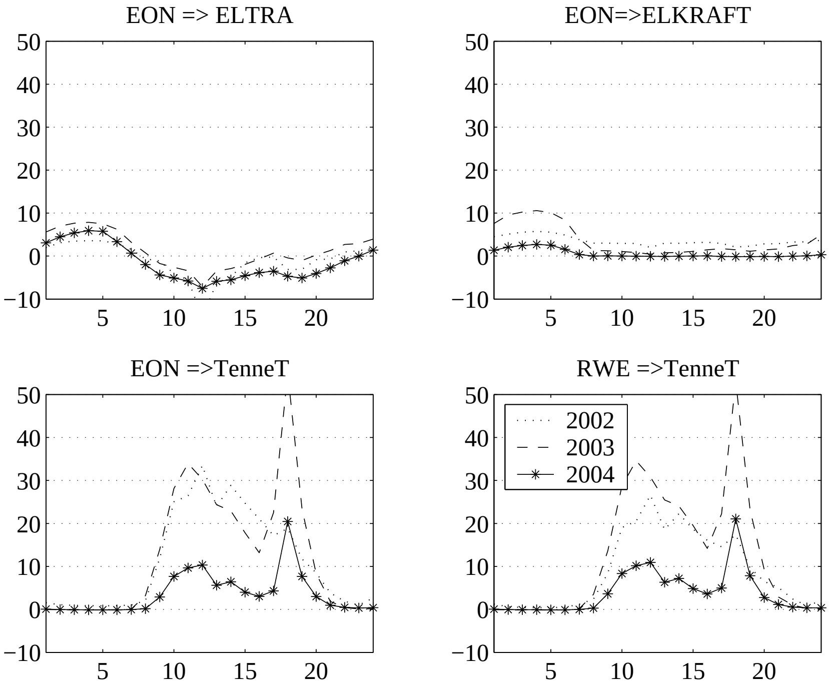
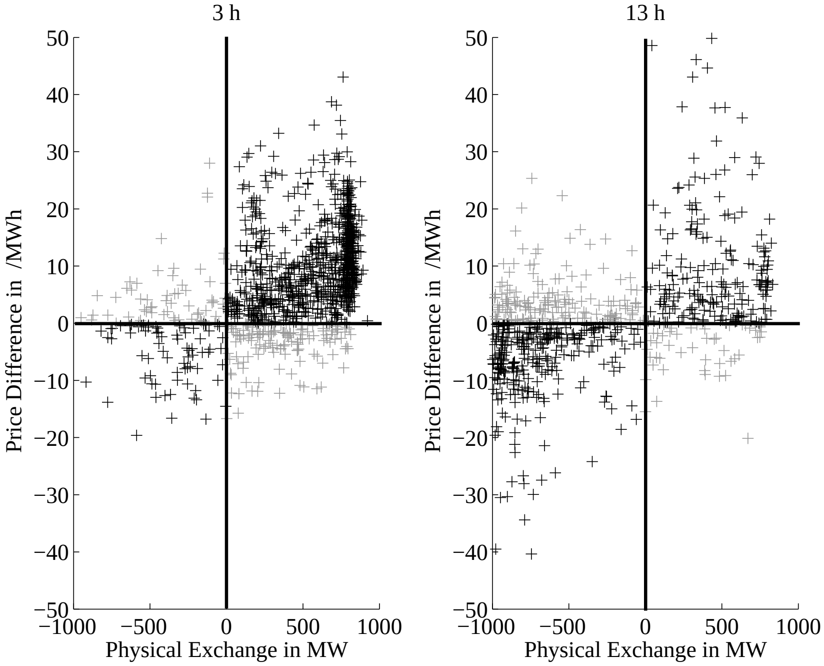


Figure 4: EEX-DKW price differential and associated physical flows between West Denmark and Germany 2002-2004



Dutch transmission system operator (TSO). From the German side, two TSOs (RWE and EON) maintain cross-border transmission lines with the Dutch grid. Therefore, TenneT calculates the prices for both interconnections (EON-TenneT and RWE-TenneT) separately. Figure 3 indicates that auction results at both interconnections are almost equal on average. Because only one German spot price is available, the RWE-TenneT interconnection is omitted in the analysis.

Figure 4 shows, using the example of the West Danish-German border, that electricity relatively often flows from high-price to low-price areas (gray crosses), which is counterintuitive. These deviations can hardly be explained by loop flows, because West Denmark is a peninsula. If long-term contracts were responsible for this unusual behavior, this would imply that domestic arbitrage is imperfect. Another reason for the deviation from economic intuition could be the uncertainty arising from the timing of the day-ahead price-setting processes.

Table 2 illustrates the auction process. First, the transmission capacity

Figure 5: Yearly average arbitrage opportunities

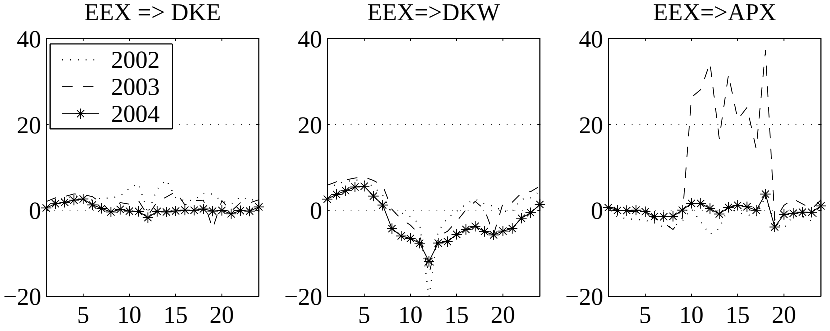


Table 2: Timing of cross-border auctions and spot markets

	Cross-Border Auctions		Power Exchanges		
	EON-TenneT	EON-ELTRA	APX	Elspot	EEX
Announcement of ATC	8:30	9:00			
End of bidding	9:00	9:30	10:30	12:00	12:00
Publication of results	9:30	10:00	11:00	12:00	12:15

available in the daily auction is announced, then bids are submitted, the auction is closed and the results are published. While the transmission capacity auction is taking place the power exchanges are collecting bids and selling offers. A certain time after the capacity auction results are published, power exchanges close the bidding, calculate spot prices and publish them. Therefore, a trader aiming to do arbitrage by selling cheaper German power to the Netherlands has to first bid on transmission capacity without knowledge of the exact spot prices, then submit his sell offer for electricity in Amsterdam knowing only the transmission auction results. After receiving the APX price, the transmission capacity price and the quantities purchased, he can now bid for German power at the EEX.[13]

From the example described above, it is clear that explicit auctions do not always result in (full informational) arbitrage freeness. However whether or not there are fundamental distortions is another question. We calculate

---

[13] Note that this example ignores that the trader might be in the possession of long-term contracts in one or more of the three markets.

the difference between the yearly average of the daily transmission auction prices and the yearly average of the spot price differentials for each hour of the day. Figure 5 provides clear evidence of the existence of arbitrage opportunities[14] between German and Dutch as well as German and Danish prices. However, comparing the yearly averages also indicates that the inefficiencies have decreased over time. This might be explained by improved legislative and regulatory frameworks, learning processes being undergone by the market participants, or both. Although Figure 5 is able to provide initial insights and a comprehensive graphical representation of the development of cross-border arbitrage possibilities, simply averaging over the year tends to neglect a wealth of valuable information. Over the course of the year, periods where exporting or importing provides arbitrage opportunities might balance each other out, the effect of events like a transmission line closure might disappear and other intra-year patterns might remain undetected. Therefore, an approach providing more differentiated results is applied in the next section.

3 Method and Results

The starting point for the analysis of the efficiency of markets is usually the law of one price (LOP). The LOP states that two similar commodities, when offered at the same location, have the same price. In theory the LOP should apply to wholesale electricity spot prices, too. However, there are several factors that lead to deviations from price equalization. The hypothesis to be tested in our analysis is that some of the reasons for these inefficiencies were removed or alleviated as a result of the ongoing electricity sector reforms, and thus, prices converged in the period under consideration. The analysis is carried out in three steps: *First*, a time-variant coefficient (α_t) representing the difference between domestic and import prices is estimated. *Second*, a proximity index is calculated, indicating the closeness of the observed prices to the LOP. And *third*, the speed of convergence towards the LOP is calculated by estimating the slope of the proximity trend index.

When comparing the prices of goods at different locations, the costs associated with transport have to be included in the analysis. Therefore arbitrage freeness is given if the price in the exporting country plus the transmission cost is equal to the price in the importing country. This relationship is

---

[14] Here arbitrage opportunities are:
$|\text{ domestic price}_t - \text{foreign price}_t - \text{import cost}_t + \text{export cost}_t| > 0$.

formalized in (1) for the example of German and Dutch prices. Here the variable $\text{transm}_{EEX->APX,t}$ is the congestion fee for one MWh flowing from Germany to the Netherlands. In the full information case considered, either $\text{transm}_{EEX->APX,t}$ or $\text{transm}_{APX->EEX,t}$ is zero.[15]

$$p_{EEX,t} + \text{transm}_{EEX->APX,t} = p_{APX,t} + \text{transm}_{APX->EEX,t} \tag{1}$$

In reality, there are several factors that may lead to deviations from the LOP, e.g. uncertainty, line failures, market power and regulation. To be able to analyze whether prices converged towards the LOP in the long run, the deviations from the LOP have to be separated into a short-term idiosyncratic and a long-term systematic component. For this purpose time-varying coefficient models provide an adequate framework.[16]

$$\begin{aligned} y_t &= \alpha_t \cdot x_t + \epsilon_t \\ \alpha_t &= \alpha_{t-1} + \upsilon_t \end{aligned} \tag{2}$$

with:

$$\begin{aligned} y_t &= p_{i,t} \\ x_t &= p_{j,t} + \text{transm}_{i->j,t} - \text{transm}_{j->i,t} \\ i, j &= \text{APX, EEX, DKE, DKW} \end{aligned}$$

were $\epsilon_t \sim N(0, \sigma_\epsilon^2)$ and $\upsilon_t \sim N(0, \sigma_\upsilon^2)$ are white noise processes and α_t is the vector of unobservable coefficients at time t. The idea behind (2) is that the coefficient α_t be allowed to change smoothly over time. Thus (2) is well suited to model long-run convergence processes. As described in Hamilton (1992 p.399 ff)[17] time-varying coefficient models such as (2) are estimated using the Kalman Filter. Although multiple setups for this filter have evolved over time, the general idea of this algorithm to subsequently predict the next period's observation, compare this forecast with the realization and include the

---

[15] In the real world, cross-border transmission capacity auctions often end up having positive prices in both directions, which is a clear sign of market inefficiencies (e.g. incorrect spot price forecasts, inner-market frictions caused by market design or market power). Such departures from our trade model are no flaw for us, since we aim at benchmarking the real world versus our perfect market model.

[16] To circumvent the colinearity problem associated with the fact that the price of the exporting country is negatively correlated with the transmission costs, a new independent variable is defined as the price in the exporting country plus the exporting and minus the importing costs.

[17] Also see Hamilton (1992) for technical details on the algorithm and its properties.

difference in the prediction for the next period was maintained in all implementations. For our purposes we found the Extended Kalman Filter (EKF) algorithm, as implemented in the ReBEL© Toolkit[18] to be an appropriate compromise among speed, accuracy and practicability. To estimate (2), assumptions on the initial variances for ϵ , υ and α_0 as well as on the expected value of α_0 have to be made. Setting $E(\alpha_0) = \frac{y_t}{x_t}$ is straightforward whereas deciding on the variances is less intuitive. Generally the initial variances can be interpreted as the starting point of the search for the global extrema of the likelihood function. Therefore, if the function has several local maxima, a "wrong" starting point can lead to undesirable results.[19] Although in general this decision can be of great importance, numerous sensitivity tests suggest that our results are robust with respect to the initial variances.[20]

Another issue one has to address when estimating (2) is which time series to use. To be able to distinguish peak from off-peak developments, we estimate (2) for each hour of the week-days series. By doing so, peak time (9-21h) and off-peak time (22-8h) can be clearly distinguished. Finally, the α_t are estimated for each hour of the day separately using the specifications of the EKF described above. Due to the lack of hourly transmission prices for most of the borders, (2) can only be estimated for the German - Dutch (EEX-APX), the German - West Danish (EEX-DKW) and the German - East Danish (EEX-DKE) border.

The results depicted in Figure 6 clearly show periods of price equalization and periods of price divergence. Some of the latter can be explained by transmission line failures, for example the closure of the Kontek direct current cable between East Denmark and Germany that caused enormous deviations from the LOP in early 2003.[21] Other periods of deviations are the result of

---

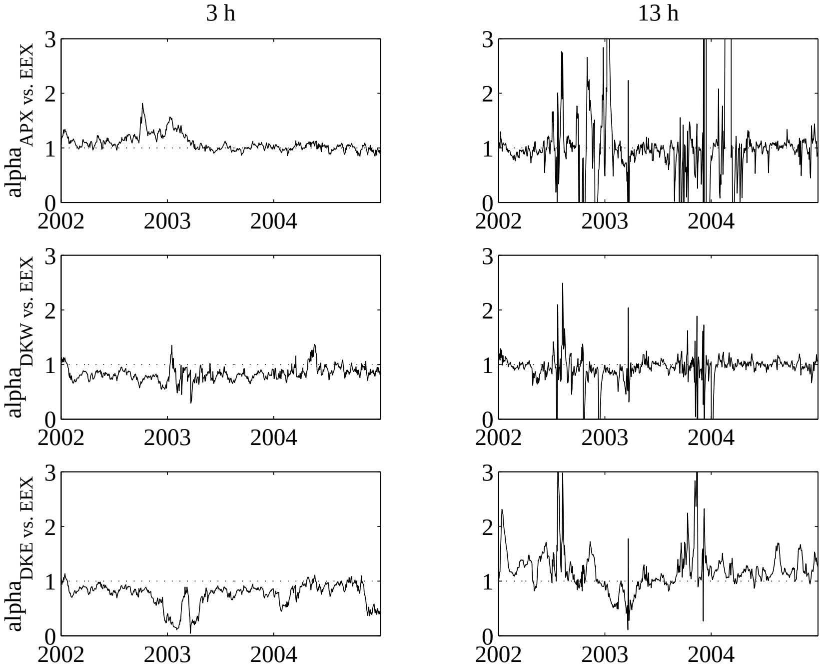
[18] ReBEL: Recursive Bayesian Estimation Library - A Matlab toolkit for Recursive Bayesian Estimation. Copyright 2002, Rudolph van der Merwe at the OGI School of Science & Engineering at OHSU (Oregon Health & Science University).

[19] This is why the initial variances should be selected with care. The tradeoff can be described as follows: Using too-high values for $\sigma^2_{\alpha_0}$ and σ^2_{υ} would lead to the inclusion of short-term behavior in α_t which would make it difficult to distinguish idiosyncratic shocks from systematic patterns. On the other hand, setting a low variance for υ_t would lead to ignoring significant developments in the convergence process.

[20] Finally we adjusted the initial variance of ϵ_t to 1 and υ_t to 0.0001 times the variance of $y_t - x_t$. Note that adjusting these values up or down by factor 100 does not change results as long as σ^2_{ϵ} remains 10,000 times bigger than σ^2_{υ}.

[21] From 4th to 28th of January 2003, the Kontek line was closed due to a cable malfunc-

Figure 6: Time-variant coefficient (α_t) for the German (EEX) - Dutch (APX) and German (EEX) - Danish (DKE, DKW) borders for the 3rd and 13th hour



national price spikes that did not lead to higher cross-border transmission capacity prices. Whether uncertainty or other factors are responsible for these repeated market failures remains unclear. The overall picture does, however, show slight convergence.

To get a more precise idea of the convergence process, we also construct an indicator for the proximity of markets using the filtered coefficients. This is done by inverting all α_t that are greater than one:

$$\gamma_t = \begin{cases} \hat{\alpha}_t & \text{if } \hat{\alpha}_t < 1, \\ 1/\hat{\alpha}_t & \text{if } \hat{\alpha}_t \geq 1. \end{cases} \tag{3}$$

The proximity indices (γ_t) are depicted in Figure 7 together with their trend line. The slope of the trend line (θ) is a one-number summary of the convergence or divergence of each pair of the two markets.[22] A significantly positive θ points to convergence of the price series towards the LOP by indicating that formerly existing arbitrage opportunities diminished over time. Testing the significance of θ is not straightforward since the usual Student-distribution does not apply because γ_t is not normally distributed.

Therefore, the critical values for the test statistic were calculated via simulation. For this purpose, we first created n artificial vectors of $\tilde{\gamma}_{t,i}$ for every hour and every combination of countries by estimating (2) and (3) for synthetic observation and state series.[23] Then, for each vector of $\tilde{\gamma}_{t,i}$ we calculated the t-value for the null-hypothesis that θ equals zero. By comparing the t-value of the θ for the real data with the t-value of the $\tilde{\theta}_i$ for

---

tion on the German side. Despite bad weather, Vattenfall immediately started to repair the cable because of high prices following water shortages in the Nordel area. [Source: http://www.udo-leuschner.de/energie-chronik/030212.htm]

[22] The results are summarized for all hours of the day in Table 6 in the appendix.

[23] To generate the artificial values of α_t and y_t we apply the residuals bootstrapping methodology (see Chernick (1999 pp. 76-78)). This is done separately for every hour and every combination of countries because the distribution of the test statistics depends on the statistical features of each single series. In all cases the independent series $\tilde{x}_{t,i}$ are given by the original data x_t. The initial state variable $\tilde{\alpha}_{0,i}$ is drawn with replacement from the estimated $\hat{\alpha}_t$. The error terms $\tilde{v}_{t,i}$ for the state equation are drawn with replacement from $\hat{\alpha}_t - \hat{\alpha}_{t-1}$. Thus n artificial state variables are calculated by $\tilde{\alpha}_{t+1,i} = \tilde{\alpha}_{t,i} + \tilde{v}_{t,i}$ for n random draws of $\tilde{\alpha}_{0,i}$ and $(n \times t)$ random draws of $\tilde{v}_{t,i}$. To create synthetic values of the dependent variable y_t we follow the same methodology drawing with replacement $\tilde{\epsilon}_{t,i}$ from the residuals of $y_t - x_t$ and using them together with $\tilde{x}_{t,i}$ and the artificial values of $\tilde{\alpha}_{t,i}$ to calculate $\tilde{y}_{t,i} = \tilde{\alpha}_{t,i}\tilde{x}_{t,i} + \tilde{\epsilon}_{t,i}$.

Table 3: Number of significantly converging hourly series between 2002 and 2004 at the 10% significance level

	APX-EEX	DKE-EEX	DKW-EEX
Convergence towards the LOP	12	0	19

the artificially generated series one can now determine the level of significance of the slope.

As Table 3 shows, for more than half of the hours of the day, the Amsterdam (APX) and Leipzig (EEX) prices as well as the West Danish (DKW) and German (EEX) prices converged towards arbitrage freeness in the sample period. This strongly supports our hypothesis that changes in the framework conditions as well as market participants' adaptation to these changes had the effect of moving prices towards their allocation-optimal value. The highest rates of convergence are to be found at the West Danish - German border. Since spot price differentials between EEX and DKW did not fall significantly, the effect can be attributed to improved behavior of the transmission capacity market participants as well as some optimizations of the auction procedure that were implemented in the period under observation.[24] The relatively high speed of convergence at the West Danish - German border is particularly surprising because the initial level of arbitrage was already been relatively advanced.[25] Thus transmission capacity prices between West Denmark and Germany are now close to being efficient.

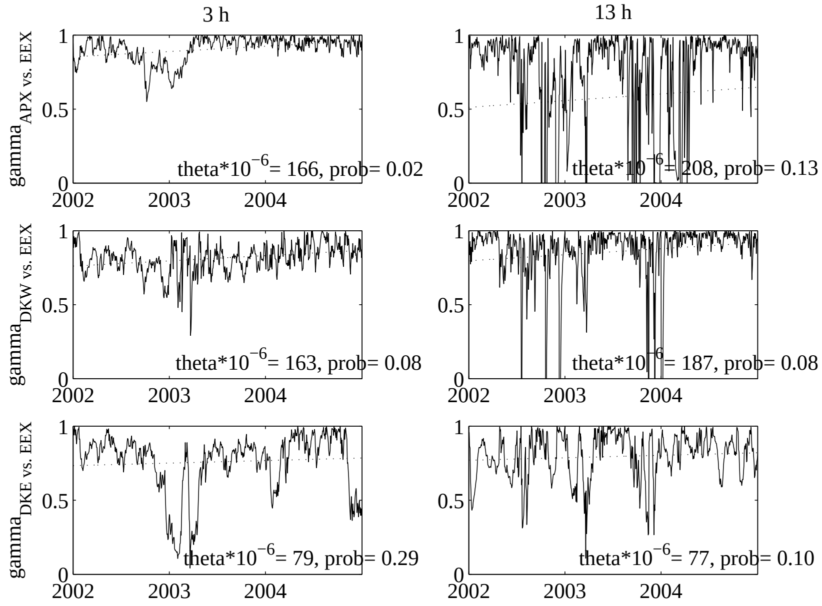
Convergence towards the LOP is less apparent for the German - Dutch interconnection since in the sample period, only 12 hourly series at this border converged. The absence of significant progress towards efficient pricing between the 9th and the 19st hour can be explained by the enormous price spikes occurring in the years 2002 to 2004 on the Amsterdam market during peak-periods. These extreme price fluctuations led to high uncertainty for market participants, who consequently found it more difficult to predict

---

[24] Beginning of April, 2002, FTP via ISDN became the main way of providing the schedules and the bids instead of e-mail. E-mail is used as secondary alternative. Beginning on June 2003 a pro-rata allocation of the rest capacity (several requests with the same price bid exceed the available capacity) was introduced and the timetable was tightened. [Source: Rules for the Daily Auction of Transmission Capacity at the Danish - German Transmission Border]

[25] As indicated in Table 7, the average intercept for DKW-EEX was 0.83, whereas the average intercepts for DKE-EEX was 0.80.

Figure 7: Proximity indices (γ) and convergence indicators (θ) for the German - Dutch, the German - West Danish and the German - East Danish border at the 3rd and 13th hour



the forthcoming arbitrage possibilities and were thus incapable of bidding correctly at the capacity auctions. By way of contrast, all prices between the 20th and the 8th hour converged towards the LOP and congestion prices came close to reaching efficient levels.

In contrast to the West Danish - German and the Dutch - German border, the East Danish - German prices do not exhibit significant signs of convergence. For their behavior, we find three main explanations to be plausible: *First*, the East Danish - German interconnection links two asynchronously operating transmission systems, namely the UCTE and Nordel, which are characterized by moderately differing production structures and thus price patterns. *Second*, there exists only one cable (the Kontek undersea line) between the two countries which has been subject to various planned and unplanned closures in the sample period.[26] And *third*, auction design and market power might be partly responsible for the fact that the cross-border capacity auctions so often did not determine the economically efficient scarcity rents.

After having seen that at the three borders, prices moved at different paces towards arbitrage freeness one now can ask how this process took place. Figure 7 gives the visual impression that convergence advanced steadily but was constantly interrupted by temporary setbacks. This leads us to conclude that the main driving force for convergence was not the implementation of new rules but the gradual adaptation of market players who continuously learned how to use (and thus reduce) the remaining arbitrage possibilities.

4 Conclusions and Policy Implications

Using a time-varying coefficient model, we show that in recent years, the unused arbitrage opportunities in electricity trade between West Denmark and Germany as well as between the Netherlands and Germany have diminished significantly. This is an indication that sector reforms, the implementation of market-based congestion management methods and the adaptation of the market participants to the new framework have succeeded in decreasing market inefficiencies. We find evidence that the market participants' adaptation has been the main driving force behind the gradual convergence process.

---

[26] Another explanation, the difficulty of reversing the power flows in a single-line system, is not satisfactory, since usually in HVDC (high voltage direct current) lines (like the Kontek or the Baltic cable) the direction can be switched within a few seconds.

Despite this good news, our analysis provides evidence that the extreme price spikes on the Dutch market during peak-periods caused considerable uncertainties for market participants, who were thus unable to achieve near-zero arbitrage. Moreover it has been shown that the East Danish - German cross-border capacity auctions did not improve their ability to determine the economically efficient scarcity rents in the years 2002 to 2004.

Thus the examples analyzed demonstrate that although some progress in the efficiency of cross-border electricity trade has been made, a single European market for electricity is still far off. Therefore an increasing liquidity of spot and transmission capacity markets, a rising number of wholesale market participants and improving methods of market based congestion management are needed to further promote the convergence process. Furthermore, the reduction of physical bottlenecks remains an important prerequisite for European electricity market integration.

References

Arciniegas, I., Barrett, C., Marathe, A., 2003. Assessing the efficiency of US electricity markets. Utilities Policy 11(2), 75-86.

Armstrong, M., Galli, A., 2005. Are day-ahead prices for electricity converging in continental Europe? An exploratory data approach. CERNA Working Paper.

Boisseleau, F., 2004. The role of power exchanges for the creation of a single European electricity market: market design and market regulation. Delft University Press, Delft.

Borenstein, S., Bushnell, J.B., Wolak., F.A., 2002. Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market. American Economic Review 92(5), 1376-405.

Bower, J., 2002. Seeking the Single European Electricity Market: Evidence from an Empirical Analysis of Wholesale Market Prices. Economics Working Paper Archive at WUSTL.

Bunn, D.W. (Ed.), 2004. Modelling Prices in Competitive Electricity

Markets. John Wiley & Sons, Chichester.

Chernick, M.R., 1999. Bootstrap Methods, A Practitioner's Guide. John Wiley & Sons, New York.

CONSENTEC, 2004. Analysis of Cross-Border Congestion Management Methods. Study commissioned by the European Commission (DG Energy and Transport).

De Vany, A.S., Walls, W.D., 1999. Cointegration analysis of spot electricity prices: insights on transmission efficiency in the western US. Energy Economics 21, 435-448.

EBRD, 2004. Transition Report 2005. European Bank for Reconstruction and Development, London.

EC, 2005. Report from the Commission on the Implementation of the Gas and Electricity Internal Market (4th Benchmarking Report). Commission Staff Working Document, Brussels.

ETSO, 2004. An Overview of Current Cross-border Congestion Management Methods in Europe. European Transmission System Operators, Brussels.

Fama, E.F., 1970. Efficient Capital Markets: A Review of Theory and Empirical Work. Journal of Finance 25, 383-417.

Huisman, R., Mahieu, R., 2003. Regime jumps in electricity prices. Energy Economics 25, 425-434.

Jackson, J.E., 1991. A User's Guide to Principal Components, John Wiley & Sons, New York.

Jerko, C.A., Mjelde, J.W., Bessler, D.A., 2002. Dynamic Interactions in the Western United States Electricity Spot Markets. Dept. of Agricultural Economics at Texas A&M University.

Knittel, C.R., Roberts, M.R., 2004. An Empirical Examination of Restructured Electricity Prices. Duke University, University of California.

Lucia, J.J., Schwartz, E.S., 2001. Electricity Prices and Power Derivatives: Evidence for the Nordic Power Exchange. Review of Derivates Research 5(1), 5-50.

OXERA, 2003. Energy Market Competition in the EU and G7: The Relative Extent of Energy Market Competition in the EU and G7. Report on Behalf of the UK Department of Trade and Industry, London, Oxford.

Popova, J., 2004. Spatial Pattern in Modeling Electricity Prices: Evidence from the PJM Market. West Virginia University Working Paper.

Stoft, S., 2002, Power System Economics: Designing Markets for Electricity. John Wiley & Sons, New York.

Videbeck, S., 2004. Economic Market Segmentation of an Electricity Pool. New Zealand Institute for the Study of Competition and Regulation Victoria University of Wellington.

Vehviläinen I., Pyykkönen, T., 2005. Stochastic factor model for electricity spot price - the case of the Nordic market. Energy Economics 27, 351-367.

Worthington, A., Kay-Spratley, A., Higgs, H., 2005. Transmission of prices and price volatility in Australian electricity spot markets: a multivariate GARCH analysis. Energy Economics 27 (2005) 337- 350.

A Appendix

Table 4: ADF-test results for the wholesale spot prices of each hour of the day[27]

	APX	DKE	DKW	EEX	OTE	PNX	PPX	SWE
1h	-17.64	-4.98	-17.26	-15.71	-17.76	-15.53	-17.84	-4.67
2h	-15.90	-6.13	-17.09	-16.17	-17.10	-15.48	-16.22	-4.94
3h	-15.51	-6.72	-18.07	-15.45	-16.88	-14.57	-13.02	-5.46
4h	-15.07	-6.43	-18.09	-15.64	-17.65	-14.36	-13.22	-5.42
5h	-15.53	-6.31	-17.92	-15.78	-15.34	-15.09	-14.24	-4.78
6h	-14.54	-4.88	-14.01	-15.10	-17.57	-16.45	-14.34	-4.08
7h	-13.85	-5.11	-15.35	-15.96	-17.54	-14.72	-14.99	-3.79
8h	-18.60	-12.02	-14.37	-23.58	-17.10	-16.45	-10.76	-4.98
9h	-22.86	-7.45	-25.26	-23.14	-17.82	-15.41	-12.08	-5.69
10h	-26.09	-7.43	-23.50	-19.93	-18.76	-26.53	-11.86	-5.47
11h	-20.79	-14.39	-24.48	-23.79	-19.32	-24.84	-11.82	-5.57
12h	-19.55	-15.95	-23.57	-17.91	-19.96	-22.07	-11.29	-8.61
13h	-22.18	-8.00	-22.74	-20.25	-19.19	-23.90	-11.00	-5.11
14h	-21.64	-8.62	-26.74	-20.04	-19.26	-25.84	-11.87	-4.65
15h	-19.51	-8.90	-25.41	-17.63	-19.71	-26.52	-13.18	-3.96
16h	-18.33	-6.97	-13.41	-16.76	-17.92	-28.04	-14.26	-3.80
17h	-8.85	-5.93	-11.86	-15.00	-18.52	-13.54	-14.46	-3.64
18h	-10.82	-11.08	-13.62	-19.23	-16.65	-13.16	-13.95	-6.35
19h	-16.13	-14.13	-17.00	-29.76	-16.75	-15.88	-12.21	-5.04
20h	-17.84	-6.64	-11.82	-13.42	-16.59	-15.04	-10.92	-3.89
21h	-20.39	-5.58	-10.90	-14.28	-17.81	-12.64	-10.79	-4.14
22h	-18.81	-4.70	-13.66	-13.30	-18.97	-11.58	-11.38	-3.63
23h	-14.73	-4.13	-15.15	-13.29	-19.43	-13.24	-7.99	**-3.24**
24h	-21.85	-4.43	-19.34	-11.73	-18.27	-13.02	-13.90	-3.60

---

[27] The 99% critical value for all hours is -3.46

Figure 8: Correlation of detrended first differences of spot volumes and prices 2002-2004

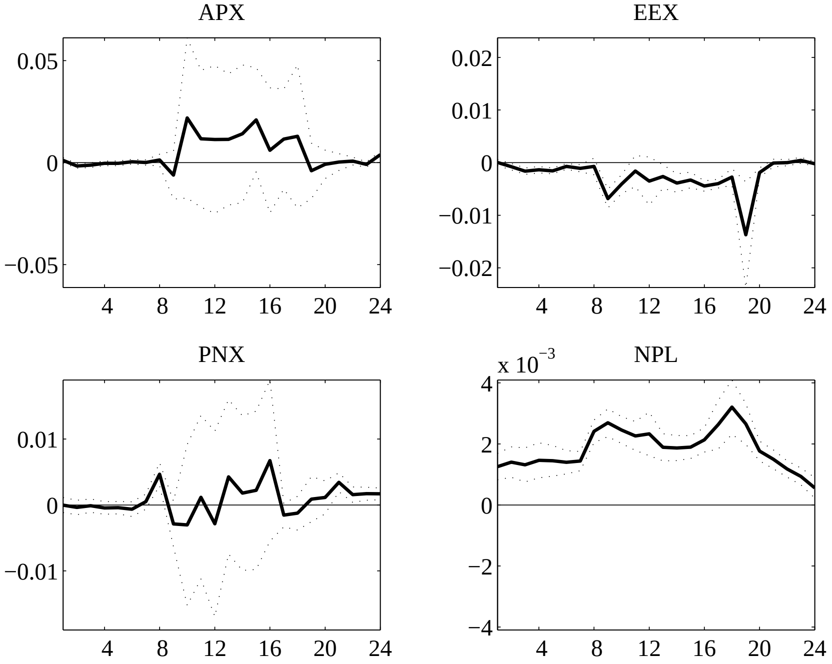


Figure 9: Correlation of detrended first differences of spot volumes 2002-2004

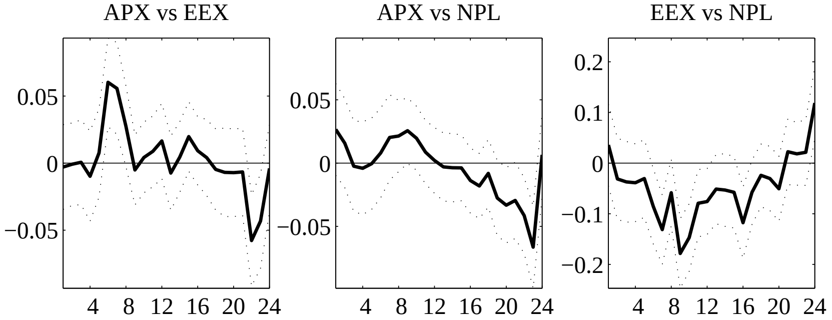


Table 5: Principal component analysis results

h	1st PC	1st& 2nd PC	APX	DKE	DKW	EEX	OTE	PNX	PPX	SWE
1	0.39	0.63	0.45	0.31	0.40	0.46	0.18	0.44	0.09	0.31
2	0.38	0.63	0.48	0.25	0.37	0.48	0.22	0.47	0.09	0.24
3	0.37	0.62	0.48	0.27	0.37	0.48	0.19	0.47	0.09	0.26
4	0.38	0.62	0.47	0.28	0.37	0.47	0.23	0.46	0.08	0.27
5	0.39	0.63	0.45	0.30	0.37	0.45	0.26	0.44	0.15	0.29
6	0.44	0.68	0.44	0.28	0.39	0.44	0.26	0.43	0.23	0.27
7	0.47	0.72	0.45	0.25	0.39	0.45	0.29	0.42	0.26	0.24
8	0.53	0.73	0.40	0.32	0.40	0.39	0.34	0.37	0.28	0.31
9	0.42	0.62	0.31	0.39	0.31	0.42	0.31	0.40	0.30	0.37
10	0.38	0.57	0.30	0.44	0.40	0.36	0.30	0.29	0.29	0.42
11	0.36	0.55	0.36	0.41	0.41	0.35	0.27	0.34	0.28	0.39
12	0.39	0.58	0.37	0.36	0.43	0.39	0.31	0.36	0.28	0.31
13	0.40	0.61	0.37	0.35	0.41	0.41	0.32	0.37	0.24	0.32
14	0.36	0.56	0.37	0.40	0.35	0.41	0.34	0.34	0.21	0.37
15	0.36	0.57	0.37	0.40	0.36	0.38	0.35	0.36	0.18	0.38
16	0.38	0.60	0.26	0.44	0.48	0.36	0.28	0.27	0.18	0.43
17	0.44	0.66	0.22	0.41	0.45	0.40	0.30	0.37	0.22	0.40
18	0.48	0.66	0.28	0.41	0.42	0.39	0.30	0.37	0.20	0.40
19	0.44	0.60	0.34	0.42	0.43	0.28	0.25	0.41	0.18	0.42
20	0.49	0.68	0.30	0.41	0.43	0.38	0.27	0.38	0.18	0.40
21	0.41	0.64	0.32	0.43	0.46	0.39	0.25	0.32	0.05	0.42
22	0.38	0.63	0.35	0.45	0.47	0.37	0.05	0.32	-0.14	0.45
23	0.38	0.62	0.33	0.44	0.47	0.41	0.01	0.30	-0.15	0.44
24	0.36	0.61	0.36	0.38	0.45	0.45	0.07	0.41	-0.06	0.37

Table 6: Growth of the convergence indicator and significance level between 2002 and 2004

	EON - TenneT (EEX-APX)		EON - ELTRA (EEX-DKE)		EON - Elkraft (EEX-DKW)	
	Growth	Prob	Growth	Prob	Growth	Prob
1h	0.09	**0.06**	0.10	0.21	0.10	**0.09**
2h	0.10	**0.04**	0.09	0.21	0.14	**0.07**
3h	0.17	**0.02**	0.08	0.29	0.16	**0.08**
4h	0.17	**0.04**	0.06	0.31	0.16	0.10
5h	0.18	**0.03**	0.00	0.36	0.13	0.13
6h	0.15	**0.03**	0.09	0.22	0.10	0.14
7h	0.19	**0.01**	0.11	0.19	0.14	**0.07**
8h	0.16	**0.05**	0.14	0.08	0.13	**0.06**
9h	0.20	0.10	0.02	0.18	0.12	**0.09**
10h	-0.51	0.30	0.02	0.20	0.17	**0.08**
11h	-1.24	0.31	0.02	0.19	0.21	**0.08**
12h	-2.07	0.56	0.11	0.12	0.16	**0.08**
13h	0.21	0.13	0.08	0.10	0.19	**0.08**
14h	0.43	0.12	0.03	0.17	0.21	**0.07**
15h	0.18	0.26	0.04	0.15	0.11	0.11
16h	-2.94	0.59	0.05	0.22	0.10	**0.08**
17h	-6.48	0.25	0.04	0.20	0.13	**0.06**
18h	-29.29	0.16	-0.00	0.18	0.18	**0.03**
19h	-5.88	0.74	0.03	0.18	0.15	**0.08**
20h	0.08	**0.08**	0.03	0.23	0.06	0.16
21h	0.13	**0.07**	0.08	0.17	0.10	**0.09**
22h	0.11	**0.05**	0.11	0.16	0.16	**0.07**
23h	0.14	**0.03**	0.13	0.13	0.15	**0.06**
24h	-	-	0.13	0.19	0.16	**0.06**

Table 7: Estimated intercept of the slope of the proximity indicator (γ)

hour	EON - TenneT (EEX-APX)	EON - ELTRA (EEX-DKE)	EON - Elkraft (EEX-DKW)
1h	0.90	0.81	0.86
2h	0.89	0.76	0.80
3h	0.85	0.73	0.76
4h	0.84	0.71	0.73
5h	0.83	0.74	0.76
6h	0.82	0.79	0.83
7h	0.81	0.83	0.85
8h	0.82	0.79	0.85
9h	0.74	0.83	0.84
10h	-0.43	0.82	0.81
11h	-0.90	0.80	0.78
12h	-2.60	0.67	0.78
13h	0.51	0.77	0.80
14h	0.26	0.80	0.78
15h	0.30	0.82	0.84
16h	-3.83	0.83	0.88
17h	-7.12	0.85	0.87
18h	-33.98	0.86	0.83
19h	-0.19	0.84	0.84
20h	0.84	0.85	0.90
21h	0.85	0.83	0.89
22h	0.88	0.84	0.85
23h	0.88	0.84	0.86
24h	-	0.82	0.84