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Electricity wholesale market prices in Europe: Convergence? ☆

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Abstract

This paper tests the hypothesis that the ongoing restructuring process in the European electricity sector has led to a common European market for electricity. Based on a Principal Component Analysis (PCA) of wholesale electricity prices in 2002–2006, we reject the assumption of full market integration. For several pairs of countries, the weaker hypothesis of (bilateral) convergence is accepted based on unit root tests (KPSS and ADF) and a convergence test based on filtered pairwise price relations. This indicates that the efforts to develop a single European market for electricity were so far only partially successful. We show that the daily auction prices of scarce cross-border transmission capacities are insufficient to explain the persistence of international price differentials. Empirically, our findings confirm the insufficiency of explicit capacity auctions as stated in the theoretical literature.

JEL classification: L94; C5; G1

Keywords: Electricity prices; European integration; Time series analysis

1. Introduction

A common electricity market is expected to increase welfare by ensuring security of supply, stimulating competition, and reaping the gains from international cooperation through such

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means as reserve sharing, combining different national consumption and production patterns, etc. To create a single European market for electricity the European Union has issued two directives, one regulation and several decisions that oblige both old and new EU member states to undertake substantial reform efforts. The measures require that: markets be opened (e.g. Directive 2003/54/EC); obstacles to cross-border trade be reduced (Regulation 1228/2003); and that non-discriminatory third-party access to the network be guaranteed (e.g. Directive 2003/54/EC). To date, implementation (via the enactment of national laws) among the member states varies. Even a cursory read of the reports benchmarking national electricity sector reforms such as EC (2005, 2006), and OXERA (2005) reveals the differences that remain. Although there has been substantial progress by some members, the EU's goal is yet far off.

Given these circumstances, several authors have wondered whether market outcomes can confirm the success of the reforms with respect to the EU's common market policy. Bower (2002), Armstrong and Galli (2003), Boisseleau (2004), Armstrong and Galli (2005), and Turvey (2006) compared day-ahead wholesale market prices at several European power exchanges. Bower (2002) applied correlation and cointegration analysis to 2001 prices from the Nordic countries, Germany, Spain, the UK, and the Netherlands. He concluded that some European electricity markets (especially the Nordic countries, the Netherlands, and its neighbors) were already integrated to a certain extent by 2001.[1] A relevant chapter in Boisseleau (2004) that focused on regression and correlation analysis determined that the level of integration of European markets is quite low. Both Bower (2002) and Boisseleau (2004) described the respective status quo of European market integration; in contrast, Armstrong and Galli (2005) analyzed the evolution of price differentials between France, Germany, the Netherlands and Spain from 2002 to 2004, concluding that European electricity prices converged in this period.[2] Turvey (2006) examined the use of interconnectors and the pricing of scarce transmission capacities. Based on the example of the Anglo-French Interconnector, he provided empirical evidence for the insufficient correlation of flows and price differentials.

International electricity price convergence[3] can be triggered by different factors, like: the convergence of factor prices; the convergence of product prices[4]; the harmonization of the institutional framework; the convergence of electricity market regulation; the convergence of production technologies and consumption patterns, as well as increasing international electricity trade. While changing investment as well as merger and acquisition behaviour will primarily have long-term impacts, rising international trade will promote market integration in the short- and medium-term. In this paper we will concentrate on the latter. Therefore we test whether European day-ahead electricity wholesale prices converged between 2002 and 2006. Showing that national prices approach over time would indicate that the single market policy was effective in the medium-term, while finding no convergence would imply the (at least initial) shortcoming of those policies.

[1] However, this result is mainly due to Bower's use of unweighted daily average data; given the strong differences between peak and off-peak price behavior on the electricity market, it is an inappropriate representation of price data.

[2] Their reasoning is based on the comparison of three yearly averages of price differentials. Because Armstrong and Galli did not perform statistical tests on the significance of their results and ignored the cross-border capacity rationing mechanisms, it remains uncertain whether their conclusions might be generalized.

[3] The term "convergence" is used throughout the text in the definition used by Engel and Rogers (2004), i.e. price convergence is the reduction of international price level dispersion over time.

[4] The Heckscher–Ohlin model, for example, predicts that factor (i.e., electricity) prices converge when product prices converge.

Table 1
Liquidity of European power exchanges

Abbreviation — power exchange (Country)	Currency	Spot market volume 2005 in TWh	Total consumption 2005 in TWh	Share of power traded spot
APX — Amsterdam Power Exchange (NL)	€	16.0	114.7	14%
EEX — European Energy Exchange, Leipzig (D)	€	85.3	556.4	15%
EXAA — Energy Exchange Austria, Graz (A)	€	1.5	63.2	2%
DKE — East Danish NordPool price area (DK)	DK	Nordpool Total:	Nordel Total:	
DKW —West Danish NordPool price area (DK)	DK	167.8	402.7	42%
SWE — Swedish NordPool price area (S)	SK			
PNX — Powernext, Paris (F)	€	19.7	482.4	4%
PPX — Polish Power Exchange, Warsaw (POL)	Zt	2.0	130.6	2%
UKPX — UK Power Exchange, London (UK)	£	8.8	407.3	2%
OMEL — Operador del Mercado Ibérico de Energía, Madrid (ES)	€	223.3	252.8	88%
OTE — Czech Market Operator, Prague (CZ)	CZK	0.4	62.7	1%

Sources: consumption: Nordel, UCTE and DTI; spot volumes: respective power exchanges.

Our paper analyzes the integration of Europe's electricity markets between 2002 and 2006 by studying the development of wholesale prices. We distinguish between the *level of market integration* – the (static) degree to which the single European market is attained – and *price convergence* — the (dynamic) measure for the development of prices toward a single European price. Unlike the empirical studies mentioned above, our paper accounts for the effects of congestion and congestion management by including the prices in the daily auctions for the use of scarce transmission capacities (so-called "congestion charges").[5]

To capture both market integration and price convergence, our line of argument consists of three steps. First, we demonstrate by means of PCA that no single European electricity market exists so far. Second, using stationarity tests, we show that several price pairs converged bilaterally in 2002–2006. Third, we provide evidence that congestion, as represented by the hourly cross-border capacity auction prices, cannot fully explain the insufficient electricity market integration observed.

2. Data

Workable, wholesale electricity markets are a cornerstone of the EU's desire to build a single, common market. Thus, most of the old and some of the new EU member states have established power exchanges in recent years. Nearly all feature a spot market on which electricity for each hour of the day ahead is traded. Thus, we can use their "on the hour" prices to examine intraday developments and compare them across markets.

Our dataset consists of information from six West European countries (Austria; France; Germany; Netherlands; Spain; and the UK); two Central European new EU member states (Poland; Czech Republic); and three North European price areas (East Denmark; West Denmark; and Sweden). The sample covers the years 2002 to 2006. This limitation to less than five years is due to the fact that liquidity in most of the considered markets was insufficient before 2002. Nevertheless, the significant changes of the electricity market framework during this period

[5] Since administrative "congestion charges" no longer exist in the UCTE, we use the term as a synonym for the prices paid in cross-border capacity auctions.

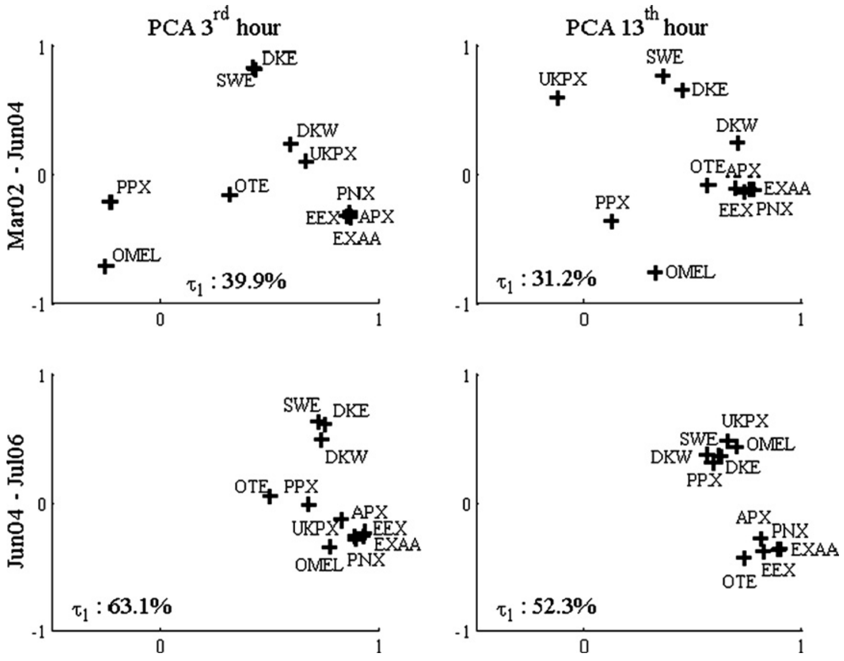

Fig. 1. Correlation of the 3rd and 13th hour wholesale spot prices with their first (*X*-axis) and second (*Y*-axis) PC and the variances explained by the first PC (τ_1).

(e.g., Directive 2003/54/EC, Regulation 1228/2003), and the high data frequency available should allow to reveal systematic developments of European electricity market integration.

Domestic electricity consumption, electricity traded on the spot market and the resulting spot market liquidity in 2005 for the eleven points (and their abbreviations) are summarized in Table 1. Since the participation in most of the wholesale spot markets is considered voluntary, their liquidity represents a relatively small fraction of domestic consumption; this is especially true for the Polish, Czech, Austrian and British day-ahead prices.[6]

Apart from the UK power exchange (UKPX), the markets feature “uniform price sealed bid one-shot day-ahead” electricity auctions. The auctioneer collects all supply and demand bids and orders them into 24 hourly bid collections. Market clearing is done once per trading day and separately for each hour; physical delivery of the sold electricity is taken on the following day. Despite minor differences in structure, liquidity, products and market mechanisms, the power exchanges in Austria (EXAA), France (Powernext), Germany (EEX), the Netherlands (APX), and Poland (PolPX) operate in similar fashion. The Nordic countries (Denmark; Finland; Norway; and Sweden) have a common power exchange called NordPool which organizes a joint spot market (Elspot). The Spanish power exchange (OMEL) is a mandatory pool leading to a comparably high liquidity. With its low liquidity of 0.6% (2005), the Czech market (OTE) is not a typical power exchange but we include it in our dataset because it provides the only available data

[6] We note that the liquidity of some electricity exchanges is quite low. Absent equally consistent data, the spot prices are usually considered as the national reference price. The economic reasoning is that if the “real” price were essentially different from the power exchange price, arbitrageurs would be inclined to buy on the cheaper and sell on the more expensive markets without any risk of forcing the prices to converge.

Table 2
Pairwise stationarity (+) or unit root (−) of *base* electricity price differential 2002–2006 according to KPSS and ADF tests

	DKW	SWE	OMEL	PNX	UKPX	EEX	OTE	PPX	EXAA	APX	#
DKE	++	+	+		−		+	−−	−	−	4
DKW			+		−		+	−−	−		3
SWE			+		−				−	−	2
OMEL							++	−		+	5
PNX						+	+	−−	++		3
UKPX								−−	−	−−	0
EEX							++	−−	++	+	4
OTE									+	++	7
PPX									−−	−−	0
EXAA										+	4
APX											4

+ : ADF rejects unit root at the 1% level and KPSS accepts stationarity at the 1% level => Convergence.
++ : ADF rejects unit root at the 1% level and KPSS accepts stationarity at the 5% level => Convergence.
− : ADF accepts unit root at the 1% level and KPSS rejects stationarity at the 1% level => Divergence.
− : ADF accepts unit root at the 5% level and KPSS rejects stationarity at the 1% level => Divergence.
− −: All other cases (including reject both and accept both) => Undecidable.

on hourly day-ahead prices from this major exporting state. Finally, the UKPX features a continuous trading period of 48 h that closes only a half hour ahead of delivery.

3. Methodology and results

3.1. Signs of convergence

We calculate the first and second principal components (PC) for the normalized data, and compute the correlation between the PCs and the original data.[7] This allows visualizing the clustering of the markets (Fig. 1). As τ_1 (the variance explained by the first PC) is significantly below 100% in all considered cases, it is evident that full market integration has not been achieved. The significant increase of τ_1 from the early (2002–2004) to the more recent (2004–2006) period both for the peak (31%→52%) and off-peak (40%→63%) implies, however, that at least some individual series approached the common European pattern. PCA thus provides general evidence that a common European price pattern is increasingly able to explain national price developments.[8]

Next, the concept of "convergence" allows us to study the intensification of integration for each pair of countries separately. Following the empirical literature (e.g. St. Aubyn, 1999; Bernard and Durlauf, 1996) one way to assess whether two price series converge is to test if the difference of the two regional series contains no unit root (i.e. if the series are cointegrated with the cointegration vector $\beta=[-1,1]$.[9] According to this approach, bilateral electricity price

[7] For technical details about PCA, see for example Jackson (1991). Detailed results can be obtained from the author upon request.

[8] Note that PCA cannot be used to explicitly demonstrate convergence since the increased ability of the first PC to explain the variance of the data is largely due to the significant (and largely exogenous) electricity price increases throughout Europe in 2004–2006.

[9] Note that the interaction of wholesale electricity prices has already been studied using cointegration analysis, e.g. by De Vany and Walls (1999).

convergence implies that the logarithmic difference in national electricity spot prices is stationary.[10] We can test stationarity using the ADF[11] and the KPSS[12] test. This combination is appealing because one can test for both divergence and convergence, since the ADF test is based upon the null hypothesis of a unit root (i.e. rejection means convergence) and the KPSS test is based upon the null hypothesis of stationarity (i.e. rejection means divergence).

The ADF test is specified according to Case 1 in Hamilton (1994 p.528), i.e. without trend and constant. In other words, we want the price differences to collapse to zero and not to some constant. Thus, the 1% critical value for long series is −2.58. The lag length is selected according to Ng and Perron (1995).[13] The KPSS test is specified without time trend, leading to a 1% critical value of 0.74. The window length is specified according to Smith and Otero (2005).[14]

Using the setup described, we test for pairwise convergence of electricity prices. Table 2 presents the results for daily average electricity prices.[15] We find that 18 pairs of prices converged, 18 diverged and 19 were insignificant — an indication that European electricity market integration was not a universal process; if it did occur, it was on a pairwise basis only. In fact, the outcomes provide evidence that convergence is predominantly driven by bilateral cross-border market integration. Whereas almost half of the prices of the directly linked markets converged (7/16), only one quarter of the none-linked markets showed significant convergence (11/39). Moreover, nine of these eleven none-linked but converging market pairs included either the Czech (5) and/or the Spanish (5) markets. We posit that convergence of the Czech price series is probably driven by increasing liquidity, which forced the OTE price to approach the “real” Czech price (which is linked to the European price via the German EEX prices). It is less obvious why the Spanish (OMEL) prices approached the Nordic (DKE, DKW, and SWE) as well as the Dutch (APX) prices.

Using unit root tests for testing convergence is not universally accepted[16] for at least three reasons. First, stationarity of the price differential can imply both full market integration and price convergence, making it impossible to distinguish whether two markets are still converging or have already integrated. Second, in situations where mean price convergence is associated with increasing volatility, the stationarity test could erroneously reject the convergence hypothesis. This is relevant to our analysis because electricity prices and thus the volatility of the difference series increased significantly during the last years. Third, in the presence of mean and variance “jumps” as well as outliers, unit root tests lack robustness. Therefore, we developed an alternative approach.

The two simple indicators for the integration of two markets are the difference of the prices in both countries and the ratio of the prices. We chose the logged ratio since it can be interpreted as the relative deviation from full integration. The gross integration measure is calculated according to:

$$\gamma^{i,j}_{\text{gross},t} = \log\left(p^i_t/p^j_t\right) = \log\left(p^i_t\right) - \log\left(p^j_t\right).$$

Thus, full integration is achieved if $\gamma^{i,j}_{\text{gross},t}=0$ for all t. The integration indicator is noisy and characterized by many significant outliers because of the high volatility of hourly prices. To

[10] i.e. $\text{Var}(\log(p^i)-\log(p^j))_t=\sigma<\infty$ and $\text{E}(\log(\text{p}^i)(-\log(p^j))_t=\mu$ for $t\rightarrow\infty$.

[11] Augmented Dickey Fuller test (ADF); for details see Dickey and Fuller (1979).

[12] KPSS: for details, see Kwiatkowski et al. (1992).

[13] Starting at pmax = integer[$12*(T/100)\wedge 1/4$] we want to find out if the absolute value of the t-statistic of the last lagged difference is >1.6. If yes, we perform the unit root test; otherwise, we reduce p by one and repeat the process.

[14] Window length l = integer[$12*(T/100)\wedge 1/4$]. Note that the choice of the ADF lag length and the KPSS window length is crucial as the number of rejections decrease significantly with an increase in both measures.

[15] Note that testing stationarity separately for peak hours gives almost the same results.

[16] See for example Bernard and Durlauf (1995, 1996) and St. Aubyn (1999).

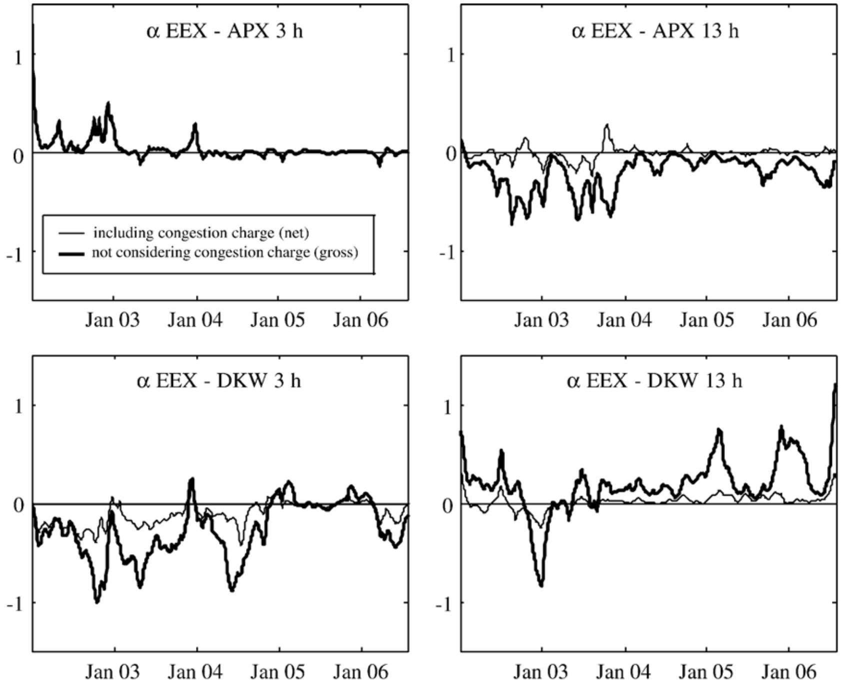

Fig. 2. Smoothed integration indicator $\hat{\alpha}_t$ for the EEX-APX and EEX-DKW borders for the 3rd and 13th hour series.

extract the long-term development of market integration, we filter out idiosyncratic and short-term developments. Time-varying coefficient models provide an adequate framework:

$$\begin{aligned} \gamma^{i,j}_{\text{gross},t} &= \alpha_t + \varepsilon_t \\ \alpha_t &= \beta\alpha_{t-1} + \upsilon_t \end{aligned} \quad (1)$$

where $\varepsilon_t \sim N(0, \sigma^2_\varepsilon)$and $\upsilon_t \sim N(0, \sigma^2_\upsilon)$ are white noise processes andα_t is the vector of unobservable coefficients at time t.

Through filtering out short-term shocks (ε_t) the estimated $\hat{\alpha}_t$ represents the long-term pattern of integration.[17] To estimate $\hat{\alpha}_t$, we must make assumptions on the initial variances for ε_t and υ_t and α_0 and on the expected value of α_0 and β. Setting $E(\alpha_0)=\gamma_1$ and $E(\beta)=1$ is straightforward but setting the variances is less so.[18] Visual inspection suggests that $\sigma^2_\upsilon=\text{Var}(\gamma_t)/100$, $\sigma^2_\varepsilon=\text{Var}(\gamma_t)$ and $\sigma_{\alpha_0}=10$ will provide an acceptable compromise in noise reduction and signal preservation. We can assure stable estimates by performing the filter and smoother algorithm up to five times using the estimated coefficients and variances as inputs for the subsequent run.

[17] As described in Hamilton (1994), time-varying coefficient models such as (1) are estimated using the Kalman filter and smoother. We use the Matlab Kalman filter toolbox by Kevin Murphy, 1998 (see http://www.ai.mit.edu/~murphyk/Software/kalman.html).

[18] 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. This is why the initial variances should be selected with care. The tradeoff can be described as follows: Using too-high values for σ^2_υ and $\sigma^2_{\alpha0}$ 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 ignore significant developments in the convergence process.

Table 3
Number of hours of the day in which the price series significantly (5%) converged/diverged when *not* correcting for hourly congestion charges (*gross*)

	Load period	PPX-OTE	EEX-OTE	EEX-PPX	EEX-PNX	EEX-APX	EEX-DKE	EEX-DKW	PNX-OME	Σ
Integration					4					4
Convergence Σ=114	Off-peak	10	8	7	5	12	10	9	11	72
	Peak	5	4		8	12			12	41
Divergence Σ=48	Off-peak			5	2		2	3		12
	Peak			12	1		11	12		36

Eq. (1) is estimated separately for each hour of the weekdays series for the German–Czech, German–Polish, German–Dutch, German–East Danish, German–West Danish, German–French, Polish–Czech and French–Spanish borders. Consequently, 192 smoothed integration indicator series were obtained. Fig. 2 (darker line) shows the third and thirteenth hour series for the German–Dutch and the German–West Danish borders.[19]

We can now use the smoothed integration indicator α_t to test whether the two prices converged/diverged. Regressing $\hat{\alpha}_t^2$ on constant (δ_1) and time trend ($\delta_2 t$) allows us to test decreases/increases in market integration. As the error terms (ξ_t) in $\hat{\alpha}_t^2=\delta_1+\delta_2+\delta_2 t+\xi_t$ are not normally independently distributed, the usual *t*-statistics do not apply for testing the null hypotheses that δ_1 and/or δ_2 are different from zero. Therefore, the table of critical values must be bootstrapped. We estimate $\hat{\delta}_1$ and $\hat{\delta}_2$ for 1000 randomly reordered series of $\gamma^{i,j}_{\text{gross},T}=(\gamma^{i,j}_{\text{gross},1}, \gamma^{i,j}_{\text{gross},2},\ldots, \gamma^{i,j}_{\text{gross},n})$.[20]

With the critical value in hand, we can now test for pairwise long-term convergence or divergence of the wholesale prices. Theoretically, full market integration is achieved if all $\gamma^{i,j}_{\text{gross},T}$ are indistinguishable from zero. We assume full integration of market *i* and *j* if none of the $|\gamma^{i,}_{\text{gross},T}|$ are larger than a half standard deviation of the (more volatile) underlying log electricity price series. Following this notion, we observe that the German–French market was integrated in the sample period for 4 h (1 h, 2 h, 10 h and 17 h). The integration of the two biggest Continental wholesale markets in two off-peak and two shoulder hours (between peak and off-peak) confirms the strong correlation of both markets that we obtained using PCA.

Convergence toward full integration is assumed if the null hypotheses $\delta_1 \leq 0$ and $\delta_2 \geq 0$ can both be rejected. The results summarized in Table 3 reveal that while the gross price differentials between France and Spain and between Germany and the Netherlands decreased in all hourly series, gross convergence in the Polish–Czech, German–Czech, German–Polish and both German–Danish cases was primarily an off-peak period phenomenon. We found that 113 of the 192 hourly pairs of price series converged between 2002 and 2006. This indicates that the degree of market integration generally increased during this period of active market development.[21] The fact, however, than more than one third of the price series pairs did not converge during these five years raises doubts on the effectiveness of the implemented market reforms.

If the null hypotheses $\hat{\delta}_1 \leq 0$ and $\hat{\delta}_2 \leq 0$ can both be rejected, the price series diverged pairwise; we found this for 48 of the 192 series.[22] In fact, almost all of the German–East Danish,

[19] The results for all studied country combinations and hourly series can be obtained from the author upon request.

[20] This task is arduous in terms of computing time since it must be performed separately for all studied pairs of countries as well as for all hours (192 series) to capture the statistical features of each series of $\gamma^{i,j}_{\text{gross},T}$.

[21] The obvious volatility of the convergence process (see Fig. 2) does, however, not allow concluding that the observed convergence occurs at constant speed or will be non-reversible.

[22] Consequently, 27 series showed no significant signs of convergence or divergence, or attained full integration.

Table 4
Cross-border congestion management method in the sample period (1/2002–8/2006)

	DKW	SWE	EEX	UKPX	OMEL	APX	PPX	EXAA
DKE	IA	IA	<2005 EA >2005 IA					
DKW		IA	EA					
PNX			<2005 NMB >2006 EA	EA (only base)	<2005 NMB >2006 EA			
EEX		AL (merchant line)				EA	<2005 EA* >2005 CEA	NMB (no congestion)
OTE			<2005 EA >2005 CEA				<2005 EA* >2005 CEA	<2005 EA* >2005 EA

EA: Explicit Auction; EA*: Explicit Auction without day-ahead auctions; AL: Access Limitation; CEA: Coordinated Explicit Auction (Poland; Czech Republic; Germany) IA: Implicit Auction; NMB: Non-market based (e.g. pro rata; priority list); The table roughly summarizes ETSO (2004, pp. 5–7) and ETSO (2006, pp. 7–10) where more detailed information can be found.

German–West Danish and German–Polish peak price series diverged significantly. The higher frequency of gross convergence in off-peak (72 vs 41) and divergence in peak (12 vs 36) is explained by the scarcity of transmission capacity, when congestion and gross price differentials are more distinctive in high-load periods. The effect abates when congestion charges are included (see next section).[23]

3.2. Including congestion charges

Despite very active international trading in Europe, the results of both the PCA and stationarity tests indicate that market integration is far from being achieved.[24] The persistence of international price differentials is often justified by the scarcity of cross-border transmission capacities. Capacity allocation (also termed "Congestion Management Methods") varies throughout Europe, and occasionally changed in the most recent years (see Table 4). Some of the variations include: priority lists (used by France and Germany before 2006); explicit auctions (between Germany and the Netherlands); and implicit auctions (NordPool).[25] Regulation 1228/2003 forbids the use of non-market-based congestion management methods such as "first come, first serve" or "pro rata." Since 2006, however, almost all European cross-border capacities are auctioned either implicitly (NORDEL area) or explicitly.

In *implicit auctions* a market operator collects bids and offers for electricity deliveries in several regions and calculates regional prices accounting for any regional line limitations. If the transmission capacity between two areas becomes binding, the prices in both regions will differ.

[23] Comparing the sums of hourly series converging ignores the fact that adjacent hourly series are highly correlated. To assure the stability of the results presented in Tables 3 and 5, we tested for convergence of four six-hourly blocks. The outcomes confirmed the validity of the findings obtained using hourly series.

[24] Market integration can be triggered by the following factors: (1) an adjustment of factor prices, e.g. fuel prices, emission cost, interest rates and wages; (2) the adaptation of a common institutional framework, e.g. emissions trading scheme, pollution prevention legislation, taxes or safety standards; (3) the convergence of electricity market regulation; (4) common production and consumption patterns, e.g. due to shared weather phenomena, resource endowments or fuel supplies; and (5) international electricity trade. The last factor stands out as it can prompt full market integration independently from the other aforementioned causes.

[25] The advantages and disadvantages of these methods are discussed in CONSENTEC (2004) and ETSO (2006).

Table 5
Number of hours of the day in which the price series significantly (5%) converged/diverged when correcting for hourly congestion charges (*net*)

	Load period	PPX-OTE	EEX-OTE	EEX-PPX	EEX-PNX	EEX-APX	EEX-DKE	EEX-DKW	PNX-OME	Σ
Integration				1	11					12
Convergence Σ=105	Off-peak	6	9	8	2	11	12	11	2	61
	Peak		11	1		9	8	11	4	44
Divergence Σ=28	Off-peak	1		3	2				1	8
	Peak	7		4	3		2		4	20

Consequently the congestion charge equals the price differential. In *explicit auctions* market participants can buy and sell electricity in all regional markets but must always ensure that they acquire the necessary number of transmission rights. The rights are usually allocated in annual, monthly and daily auctions for each flow direction separately. Thus, if transmission demand exceeds line capacity we would expect the capacity auction price to be above zero and electricity prices in the linked markets to differ by exactly the auction price; otherwise, traders could make risk-free profits.[26]

To include these congestion charges in the analysis, we collected the results of the daily cross-border capacity rights auctions for eight intra-European borders (France–Spain; Germany–Netherlands; Germany–Poland; Germany–Czech Republic; Germany–France; Germany–West Denmark; Germany–East Denmark; Poland–Czech Republic). These day-ahead auctions provide separate prices for all 24 h of the subsequent day. As these hourly congestion charges are based on approximately the same set of available information as the corresponding electricity spot prices, an analytic comparison is straightforward.

To asses the impact of explicit auctions on cross-border price dispersions, we construct a net integration measure by subtracting the congestion charges in the profitable direction ($c_t^{j\rightarrow i}$) from the more expensive price:

$$\gamma_{\mathrm{net},t}^{i,j} = \begin{cases} \log\left(p_t^i - c_t^{j\rightarrow>i}\right) - \log\left(p_t^j\right) & \text{if} \quad p_t^i > p_t^j \\ \log\left(p_t^i\right) - \log\left(p_t^j - c_t^{i->j}\right) & \text{if} \quad p_t^i > {}^{j}_{p} \end{cases}.$$

We interpret this indicator as: the remaining arbitrage possibility from either undertaking a cross-border trade at date t if the auction price is below the international price differential; or rejecting a cross-border trade if the auction price is above it. In reality the arbitrage freeness condition $\gamma_{\mathrm{net},t}^{i,j}=0\,\forall\, t$ can be fulfilled in implicit auctions since $c_t^{j->i}=\max\,(p_t^i-p_t^j,\,0)$ holds by definition. In explicit cross-border capacity auctions where the markets run subsequently, players face uncertainties in capacity offered, congestion charges and price differentials.[27] Because of the

[26] This "arbitrage freeness" assumption is based upon the reasoning that traders will not spend more for transporting electricity than they can gain from it (i.e. the price differential), and that underpaying cross-border capacity auctions (i.e. price differential>congestion charge) is unsustainable since the potential gain (price differential minus congestion charge) will attract other players to enter the market, forcing the prices to converge toward arbitrage freeness.

[27] If a trader wants to do arbitrage operations by selling cheaper German power to the Netherlands, it must first bid on transmission capacity without knowledge of the exact spot prices, and then submit its 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, the trader can now bid to buy German power at the EEX. Note that this example ignores the possibility that the trader might own long-term or over-the-counter (OTC) contracts in one or more of the three markets.

uncertainties in timing $\gamma^{i,j}_{\mathrm{net},t} \neq 0$ does not necessarily imply an unused arbitrage possibility in time t as players may be surprised by unpredicted price changes. Therefore unused arbitrage possibilities can only be assumed if $E(\gamma^{i,j}_{\mathrm{net},t}) \neq 0$. In this context the Kalman filter and smoother (see Section 3.1) contains an especially useful interpretation: the filtered results can be seen as the expected realization of the underlying series in $t+1$ given the series up to point t while the smoother provides the expected realization of the underlying series given the entire series. Stochastic deviations due to accidental prediction errors can be decomposed from systematic deviations. Thus, if the smoothed $\gamma^{i,j}_{\mathrm{net},t}$ is significantly different from zero, it would indicate that the price difference in t is expected to differ from zero — thus contradicting the assumption of arbitrage freeness. Applying the same testing procedure used for the gross price differential series ($\gamma^{i,j}_{\mathrm{gross},T}$) to the net price differential series ($\gamma^{i,j}_{\mathrm{net},t}$) allows us to analyze the development of unused arbitrage possibilities over time. Joint plotting of $\hat{\alpha}_{\mathrm{net},t}$ (thin line) and $\hat{\alpha}_{\mathrm{gross},t}$ (bold line) in Fig. 2 provides visual evidence that hourly congestion charges often explain only a minor fraction of the gross price differential. This is evidence that congestion is not solely responsible for insufficient market integration.

Visual inspection of the smoothed net integration indicators shows that only few series showed systematic arbitrage freeness (shown by the thin line in Fig. 2). Nevertheless some of the smoothed series approached arbitrage freeness (e.g. EEX-DKW 3 in Fig. 2). We also observe that gradual adjustments characterize the process of convergence. This indicates that continual developments in cumulative liquidity, an increasing number of traders and perpetual learning improved net market integration.[28] Hence, market reforms only gradually translate into more market integration.

Applying the same testing strategy used for the gross price differential, we found that only 12 of the 192 series showed full integration; that the price series of five markets converged in the majority of hours of the day and significant trends of net divergence were identifiable in three markets (Table 5). Thus, despite the possibility of arbitrage, more than 93% of the markets were not integrated and nearly 40% of the price series did not even converge.[29] These findings provide empirical evidence that there are significant barriers to efficient cross-border trade when capacities are auctioned explicitly.

The demonstrated inadequacy of explicit auctions to provide long-term arbitrage freeness has been assumed both in the political discussion and the theoretical literature. Ehrenmann and Smeers (2005) for example pointed out that explicit auctions will produce results inferior to those of implicit actions because of the uncertainties for traders and the different network aggregation mechanisms. In fact, trader uncertainties could be responsible for some of the detected distortions. Although the Kalman filter algorithm filtered out stochastic distortions, the uncertainties also should have led to the inclusion of a risk premium in the studied price relations.[30] An indication of the importance of a risk premium is that divergence is slightly more present in peak than in off-peak while convergence is more frequent in off-peak. This finding correlates with the hypothesis that traders desire and expect a higher risk premium for the more volatile peak-time trading

[28] Neuhoff (2003) argued that traders learned to deal with explicit auctions. He finds that while in 2001 a simple trading strategy would have generated 30.6 m Euro profits at the Dutch–German border in the first six month of 2002 only 1.2 m Euro were possible.

[29] The 40% stem from 76 neither integrated nor converging series (28 series diverging and 48 series without trend).

[30] A risk premium for traders should reward the market participants for bearing the described uncertainties of participating in explicit capacity auctions. Neuhoff (2003, p.4) describes this risk premium as an assurance: "traders price their buy bid in one market very high and their offer in the other market very low to avoid exposure to imbalance fees if only one bid is accepted."

periods. Further, it has been argued that market players may bid strategically in explicit auctions.[31] Finally, the exercise of market power may also be responsible for some distortion.

The assumed shortcomings of explicit auctions have given rise to alternative congestion management methods. Proposals for continental Europe include establishing conventional systems like nodal pricing[32] and implicit auctions as well as extending the recently implemented open-market coupling for the French–Belgium–Dutch market.[33]

4. Conclusions and policy implications

This paper provided empirical evidence that a single market for electricity in continental Europe had not been attained by mid-2006. The use of PCA revealed that in June 2004–July 2006, 48% of the peak and 37% of the off-peak price variances were not explained by the first principal component which can be interpreted as a common European price pattern.

We showed that national electricity price differences significantly diminished over time for some market pairs. Stationarity tests of wholesale price differentials indicated that price convergence was mainly driven by cross-border market integration. Studying the convergence hypothesis for smoothed hourly price differential series allowed tracing medium-term patterns as well as intra-daily differences. We found that 59% of the studied hourly pairs of national wholesale electricity prices in 2002–2006 converged. This increased market integration was mainly an off-peak phenomenon. While 64% of the converging series were in off-peak, 75% of the diverging series were in peak.

We also tested the empirical hypothesis that all remaining international price differences can be explained by cross-border transmission capacity auction prices. Arbitrage freeness is assured if the difference between cross-border price differentials and the associated transmission capacity prices is zero in expectation. We found that more than 93% of the studied market pairs featured significant predictable arbitrage opportunities but that 42% of them were not converging toward arbitrage freeness.

These findings show that the electricity market reforms in the last decade that explicitly targeted the creation of a single European market for electricity were only partially successful. We suggest that future research should include identifying the reasons for the inefficiencies of explicit auctions, such as risk premiums for traders and the exercise of market power. We believe, too, that EU policy makers should be made aware of these and other potential obstacles to the gradual realization of a common wholesale market for electricity.

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[31] See for example Neuhoff (2003) and Brunekreeft et al. (2005, p85).
[32] See for example Hogan (1992).
[33] A comparison of different congestion management methods can be found in Ehrenmann and Smeers (2005) and CONSENTEC (2004).

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