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Margherita S. Grasso

Abstract

In this paper threshold error correction models (TVECMs) and min-max (MM) models are applied to examine the integration of European electricity markets. The relationships across German, Dutch, British and French forward prices are assessed allowing for the possibility that the convergence in prices may not always be operational. Indeed, interdependences may occur only when the spread in prices between two markets makes it profitable to invest in cross-border contracts. As a main result, allowing for non-linear adjustment dynamics improves the accuracy of the model.

Keywords. Electricity, forward prices, EU market integration, non-linear error correction, min-max process.
Jel codes. C22, C32.

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1 Introduction

Along with the liberalization of power industry and the introduction of competition, electricity has become a tradable good. In Europe, the reorganization of the electricity market dates back to the 90s, and the process has been driven by the adoption of two European directives that introduced common rules for cross-country transactions to favour the creation of a common power market (Directive 96/92/EC and Directive 2003/54/EC). Recently, the approval of the ”Third package” (see Directive 2009/72/EC) has confirmed the interest of the European Union in the integration of European electricity markets, and it has paved the way for new evolution patterns.

As storage of electricity is not economically feasible, cross border exchanges are needed to cope with unbalance of internal consumption and production, ensuring the match between demand and supply. Moreover, non-storability gives rise to an increased need for risk management and futures and forward trading.

Efficiency in European spot and forward[1] markets should lead prices to move together in the long run. However, cointegration may not always be operational. This problem may be negligible for spot markets, where in absence of interconnection limits neighboring countries' prices are identical.[2] In contrast, due to heterogeneity of risks and the possibility that future spot prices differ across markets, cross-border trading of forward contracts may not give advantages when the spread in forward prices is too low. Therefore, the difference between forward prices may need to be sufficiently large for cross-border forward contracts being exchanged, leading to interdependences in prices and adjustment mechanisms. This feature can give rise to a three-regime process, in which it exists a band of non-adjustment, while a pull toward the equilibrium is operational from each outer region.

In practice, forward contracts are mainly used as hedging instruments and thus cross-border financial contracts are traded when physical exchanges of power are also possible. Moreover, due to transmission losses and regulation limits, trading is used only

[1] In what follows I will use 'forward' to mean both forward and future markets.

[2] In fact, neutral bounds may be associated with transaction and transportation costs related to cross-border spot transactions.

between countries that are neighboring or in the same regional market.
Several contributions have dealt with the integration of European prices. However, the majority of them have considered spot markets (an exception is Bunn and Gianfreda, 2009) and linear modelling (see among others Bosco et al., 2009). A non linear model approach based on regime-switching VAR models has been introduced by Haldrup and Nielsen (2009) to model spot prices in the Nordic Power market.
In this paper the relationship between cross-border forward markets is considered. Future spot prices expectations may differ across markets due to diversified production technologies and various degrees of market power coupled with limited transmission capacities. To examine whether a long-run convergence in derivative markets exists, while allowing for the possibility that cointegration may not always hold, TVECMs are used and compared to the results of an MM approach. The empirical findings support the existence of a neutral band inside cointegrated regions. This feature of cross-hedging needs to be considered when it is evaluated to what extent prices adjust to the common equilibrium.

2 Cross Integration in European Electricity Markets

As a part of the liberalization process, various national markets were opened up to cross-border trading by the creation of regional power systems. Besides the establishment of the Nord Pool [3], an agreement between France, Belgium and the Netherlands in 2006 conducted to the creation of a coordinate trading system (TLC - Trilateral Market Coupling); similarly in July 2007 an Iberian electricity market (MIBEL) was created by Spain and Portugal. Another initiative was the creation in October 2008 of a central Auction Office (EMCC) to operate market coupling between Germany and Denmark. Other actions include the agreement entered in June 2007 by five countries (Belgium, Luxembourg, the Netherlands, Germany and France) to implement a Central Western European Market Coupling (CWE MC). Moreover, the coordination mechanism

[3]Nord Pool includes Norway, Sweden, Finland and Denmark and partly Germany, and operates since early 90s

among France, the UK and Ireland has led to good results. While Nord Pool is a single power exchange, the countries in TLC, MIBEL, EMCC and CWE MC have separate markets, but with harmonized design and simplified cross-border exchanges. The creation of regional markets has been seen as an intermediate step to the building of the Internal Electricity Market (IEM) as foreseen by the directive 96/92/EC.

The sources of electricity production are rather diversified across countries. For example, in Germany fossil fuelled power plants constitute the price setting technology. In contrast, the electricity production in France is dominated by nuclear energy, which amounts approximately to 78% of total production. Per capita consumption is very heterogeneous across countries either.

When price differentials exist, there are transmissions of energy across countries, when the power grid transmission capacity is adequate to support the flow of electricity. From what stated above, there appear various reasons why the "law of one price" may not always be operational across European power markets:

The first intuition is that the "law of one price" could not apply in presence of bottlenecks: physical transmission of electricity across countries is bound by capacity constraints. Therefore, in separated power exchanges (where markets participants trade day ahead power contracts) different prices may prevail depending upon regional demand and supply conditions (see Haldrup and Nielsen, 2009).

Analysing the derivative markets, where long-term contracts are traded to manage the risk related to future price levels, it can be observed that the higher the correlation between two markets, the more effective cross-hedging strategies will be. Since sources of production and degrees of market concentration differ across countries, forward prices incorporate different cost expectations [4]. Therefore, foreign forward contracts represent an indirect hedging instrument, and the spread in two countries forward prices needs to be far enough from the equilibrium to induce investors to trade cross-border contracts to hedge risk.

[4] Given the non storability of electricity, future prices are related to fundamental expectations of future spot prices applying a forward premium that is a function of the variance and skewness of current spot prices (see Redl et al., 2009 and Bessembinder and Lemmon, 2002)

Finally, an open question is whether overall European prices tend to converge, or insufficient networks coupled with market inefficiencies prevent the 'law of one price' to prevail across European countries.
Focusing on the forward market, the main aim of the present paper is to provide an answer to the last question, while controlling for the fact that convergence in prices is possible only for sufficiently large spreads among prices. To this extent, the existence of non-linear cointegration allowing for the possibility of a band of non-adjustment is tested.

3 The econometric framework

In the present paper, three-regime vector error correction models are the basic tool used to model a situation in which the series may or may not be cointegrated depending on how far from the equilibrium relationship they are.
The idea of threshold cointegration has been introduced by the seminal paper of Balke and Fomby (1997). They assume that the cointegrating relationship, instead of being a linear function, follows a threshold autoregressive (TAR) process. The estimation procedure relies on the single equation Engle-Granger approach. Moreover, they use a two-step approach in which cointegration and threshold behaviour are tested separately.
The model has attracted considerable attention (see Lo and Zivot, 2001 for a literature review). A relevant extension of the literature is provided by Hansen and Seo (2002) that propose system estimation and testing methods of the complete multivariate threshold model. Theirs is a two-regime model defined on the equilibrium term being above or below the threshold. In the present study, their settings are modified to allow, coherently with the Balke and Fomby (1997) analysis, for a band of non-adjustment. Finally, a similar threshold cointergration could originate from the integrated min-max (MM) process introduced by Granger and Hyung (2006). Here I consider a partly linearised version of the model and adapt it to the problem at stake.

3.1 The threshold cointegration Balke and Fomby (1997) model

Let $x_{1,t}$ and $x_{2,t}$ be two $I(1)$ series that originate a cointegrated system with the error correction term given by:

$$x_{1,t} + \beta x_{2,t} = z_t \tag{1}$$

Balke and Fomby (1997) define the residuals of the above relation as:

$$z_t = \rho^{(i)} z_{t-1} + \epsilon_t \tag{2}$$

where ρ equals 1 if $r_1 < z_{t-1} \leq r_2$ and $|\rho| < 1$ if $z_{t-1} \leq r_1$ or $z_{t-1} > r_2$.
Since the β does not vary according to the regimes, the above model can be equivalently expressed in VECM form:

$$\begin{aligned}
\Delta x_{1,t} &= \mu_1^{(i)} + \lambda_1^{(i)} z_{t-1} + \sum_{j=1}^{p-1} \bar{\delta}_{1,j} \Delta x_{t-j} + \zeta_{x1,t} \\
\Delta x_{2,t} &= \mu_2^{(i)} + \lambda_2^{(i)} z_{t-1} + \sum_{j=1}^{p-1} \bar{\delta}_{2,j} \Delta x_{t-j} + \zeta_{x2,t}
\end{aligned} \tag{3}$$

where

$$\mu_m^{(i)} = \begin{cases} \mu_{m,1} & \text{if } z_{t-1} \leq r_1 \\ 0 & \text{if } r_1 < z_{t-1} \leq r_2 \\ \mu_{m,2} & \text{if } z_{t-1} > r_2 \end{cases}$$

$$\lambda_m^{(i)} = \begin{cases} \lambda_{m,1} & \text{if } z_{t-1} \leq r_1 \\ 0 & \text{if } r_1 < z_{t-1} \leq r_2 \\ \lambda_{m,2} & \text{if } z_{t-1} > r_2 \end{cases}$$

with $x_t = (x_{1,t}, x_{2,t})$ and $m = 1, 2$. Estimates of the model are obtained using conditional least squares. The support for the threshold variables is defined as $[z_L, z_U]$, where z_L ans z_U are respectively the lower and the upper values that the threshold can take, and are such that $\pi_0 \leq P(z_{t-1} \leq z_L)$ and $P(z_{t-1} \leq z_U) \leq 1 - \pi_0$. In empirical applications setting π_0 between .05 and .15 has resulted to be opportune.

3.2 The threshold cointegration Hansen and Seo (2002) VECM

Differently from Balke and Fomby (1997), Hansen and Seo (2002) consider a p-dimentional $I(1)$ time series x_t that is cointegrated with still only one $p \times 1$ cointegrating vector β. The extension of (3) to a multivatiare system takes the form:

$$\Delta x_t = A_1^{'} X_{t-1}(\beta) d_{1,t}(\beta, \gamma) + A_2^{'} X_{t-1}(\beta) d_{2,t}(\beta, \gamma) + e_t \tag{4}$$

where

$$\begin{aligned} d_{1,t}(\beta, \gamma) &= 1(z_{t-1}(\beta) \leq \gamma) \\ d_{2,t}(\beta, \gamma) &= 1(z_{t-1}(\beta) > \gamma) \end{aligned} \tag{5}$$

and $X_{t-1} = (1 \quad z_{t-1}(\beta) \quad \Delta x_{t-1} \quad \ldots \quad \Delta x_{t-p+1})'$.
To estimate (4) they propose to firstly execute a grid-search over the two dimensional space (β, γ). The empirical support for the threshold γ is defined as described above. The search region for the β is given by $[\beta_L, \beta_U]$ and is constructed over a large inteval of β (such as the asymptotic normal approximation). Parameters estimates are obtained by constrained maximum likelihood estimation. In practice:
i) Letting fixed (β, γ) for each possible value of their supports, the conditional MLE of (A_1, A_2, Σ) is obtained;
ii) The estimates of β and γ are obtained as those that minimize the negative likelihood of the model;
iii) $(\hat{A}_1, \hat{A}_2, \hat{\Sigma})$ are the estimated values corresponding to the $\hat{\beta}$ and $\hat{\gamma}$.
In specification (5) one price adjustment process applies if the deviations from the long-term equilibrium are below a threshold (regime 1) and another applies if the opposite is true (regime 2). Such a specification excludes the possibility of a ″band of non-adjustment″ of smaller deviations from a long-term equilibrium inside a regime of adjustment to bigger deviations. In this paper a more meaningful specification for the problem in question is implemented. The settings of Hansen and Seo (2002) are slightly modified by substituting 5 with:

$$
\begin{aligned}
& d_{1,t}(\beta,\gamma) = 1(|z_{t-1}(\beta)| \leq \gamma) \\
& d_{2,t}(\beta,\gamma) = 1(|z_{t-1}(\beta)| > \gamma)
\end{aligned} \tag{6}
$$

In (6) it is assumed, in line with the three-regime model of Balke and Fomby (1997), that one regime holds when absolute deviations from the long-term equilibrium are smaller than the threshold (regime 1) and another for errors that are larger in absolute values(regime 2). The model in (4) and (6) is a restricted version of a general three-regime threshold model, where $\gamma_1 = -\gamma_2$ so that no asymmetric price transmission is possible in (6), and the same price reaction occurs regardless of whether spread in prices is positive or negative[5].

To test the existence of threshold cointegration instead of linear cointegration I use the multivariate procedure proposed by HS. Given γ and β the VECM and TVECM are linear. As the former model is a special case of the latter, a LM-like statistic that is robust to heteroskedasticity can be used. Formally, the test statistic can be expressed as:

$$
\begin{aligned}
LM(\beta,\gamma) \quad &= vec\left(\hat{A}_1(\beta,\gamma) - \hat{A}_2(\beta,\gamma)\right)' \left(\hat{V}_1(\beta,\gamma) + \hat{V}_2(\beta,\gamma)\right)^{-1} \\
&\qquad\qquad \times vec\left(\hat{A}_1(\beta,\gamma) - \hat{A}_2(\beta,\gamma)\right)
\end{aligned} \tag{7}
$$

where vec is the vec operator, $\hat{A}_i(\beta,\gamma)$ are parameters estimates and $\hat{V}_i(\beta,\gamma)$ the corresponding Eicker-White covariance matrices. The LM statistic 7 is evaluated at point estimates obtained under H_0. Let the null estimate of β being $\tilde{\beta}$. The threshold γ is not defined under the null of linearity, therefore the proposed statistic is:

$$
SupLM = supLM(\tilde{\beta},\gamma) \tag{8}
$$

where the sup is with respect to γ, the search region is $[\gamma_L, \gamma_U]$ and $\tilde{\beta}$ is the linear VECM estimate of β.

[5] In fact, the advantage of easy interpretable results from a two-threshold error correction model is weakened by the fact that un to my knowledge no adequate econometric test for the significance of two thresholds has been developed (see Hansen and Seo, 2002)

To obtain the critical values and the p-values corresponding to the estimated statistic the residual bootstrap is applied. The parameters' estimates and the residuals series obtained under the null (linear VECM) are used for initializating the algorithm. The bootstrap distribution is calculated by randomly drowing from the residuals and creating new vector series x_b. The statistic supLM is calculated on each simulated sample and stored. The bootstrap p-value is the percentage of simulated statististics that exceed the actual statistic.

3.3 The MM process

The integrated Min-Max process is given by the bivariate system:

$$x_{1,t+1} = max\,(x_{1,t} + a, x_{2,t} + b) + \epsilon_{1,t+1} \tag{9}$$

$$x_{2,t+1} = min\,(x_{1,t} + c, x_{2,t} + d) + \epsilon_{2,t+1} \tag{10}$$

As it is shown by Granger and Hyung (2006) the two series above may be cointegrated even if they are two non-linearly integrated processes. Moreover, $a - d < 0$ is a sufficient condition for an equillibrium to exist. If instead of using a max-min pair, the min operator is linearized the same sufficient condition holds. Assuming that the cointegration equation is given and equal to $[1, -1]$ and definying $z_t = x_{1,t} - x_{2,t}$ the partially linearized model constitute a VECM system having:

$$\Delta x_{1,t+1} = max\,(a, b - z_t) + \epsilon_{1,t+1} \tag{11}$$

$$\Delta x_{2,t+1} = d + \epsilon_{2,t+1} \tag{12}$$

and gives rise to:

- Region(I): if $z_t \geq b - a$ then $z_{t+1} = a - d + z_t + \eta_{t+1}$, so that z_t is $I(1)$ in this region

- Region(II): if $z_t < b - a$ then $z_{t+1} = b - d + \eta_{t+1}$, so that z_t is $I(0)$.

Granger and Hyung (2006) apply the above process to analyse one risky interest rate and one risk-free rate, and their spread. While the latter is always positive, the equilibrium term between cross-country electricity prices may be positive in some periods and negative in others, which leads to opposite minimizing and maximizing behaviours. To take this fact explicitly into account (11)-(12) can be modified as:

$$\begin{aligned} \Delta x_{1,t+1} &= min\,(a^+, b^+ - z_t)\,1\,(z_t > 0) + max\,(a^-, b^- - z_t) 1\,(z_t \leq 0) + \epsilon_{1,t+1} \\ \Delta x_{2,t+1} &= d + \epsilon_{2,t+1} \end{aligned} \tag{13}$$

By subtracting Δy_{t+1} from Δx_{t+1} and using $min(-X, -Y) = -max(X, Y)$, it is obtained that:

$\Delta z_{t+1} = ((a^+ - d^+) - max\,(0, z_t - b^+ + a^+))\,1\,(z_t > 0) +$

$+ ((a^- - d^-) + max\,(0, b^- - a^- - z_t))\,1\,(z_t \leq 0)$ (13)

The adjustment mechanisms in 3.3 is illustrated in Figure 1 in the Appendix.

4 Data analysis

The data used in this paper are (logs of) baseload week-ahead electricity prices for the power exchange of the United Kingdom (UK), Germany (GE), France (FR) and the Netherlands (NE); the observations are daily records. The data set covers the period June 2005 - September 2009; for Germany the sample period starts in September 2007. The data series are displayed in Figure 3 and are reported in the Appendix.

As it can be noted, typical features of electricity prices include pronounced volatility and spikes. In this paper I do not try to average out abrupt changes, since extreme movements can contribute to make threshold models opportune to analyze electricity prices.

ADF test statistics [6] document that the log-transformed series are I(1) at the 5% level, except for French prices, where the null of unit root is not-rejected at the 1% level only. It should be noted, however, that the performed ADF tests do not allow for threshold behavior. The results are reported in Table 1.[7]

[6] The lag order in the auxiliary regression has been chosen by minimizing the BIC.

[7] Others find different results on the long memory properties of electricity prices (e.g. Haldrup and

The visual inspection of the series can give useful information about series patterns. Figure 4 in the Appendix reports the scatter plots for each couple of log-prices.
To conclude the analysis of the data, the correlations between prices in pairs are reported.
Since the figures Table 2 may have problems of spurious correlation, the correlations are calculated also for growth rates (Table 3).
The highest correlation in grow rates is between GE and FR. However, these are simple deterministic statistics and fuller interpretation requires the models to be estimated below.

5 Empirical Results

The plots in Figure 4 above show two main features:

1. The largest amount of points can be observed around a line at approximately $45°$ slope;

2. Some observations are spread elsewhere in the graphs.

Based on the first remark, a VECM seems to be a reasonable tool for analyzing the dynamics of the series and estimating the long run relationship between the prices.

Nielsen, 2009 find prices in the Nord Pool being fractionally integrated).

Variable	UK	GE	NE	FR
ADF	-2.569	2.638	-2.737	-3.343*

Table 1: **ADF test statistic** - case with intercept; the relevant critical values are -2.868 and -3.447 at the 5% and 1% levels, respectively; $*$ denotes significance at the 5% level but not at the 1%.

	UK	GE	NE	FR
UK	1.000			
GE	.856	1.000		
NE	.847	.933	1.000	
FR	.821	.928	.872	1.000

Table 2: **Correlations**

	UK	GE	NE	FR
UK	1.000			
GE	.100	1.000		
NE	.115	.236	1.000	
FR	.215	.635	.189	1.000

Table 3: **Growth rates correlations**

Efficiency in the market would imply the slope of the equilibrium relationship to be one. Whether the estimated slope of the equilibrium relationship is not significantly different from that theoretical value can then be tested.

The second observation suggests that a TVECM may be a more appropriate tool in that it allows for the possibility that the speeds of adjustment toward the equilibrium (or the existence of a cointegrating relationship) differ for data points close to the $45°$ line and observations spread farther away in the graph.

In what follows the estimates of VECM and TVECM are reported. For each pair of prices the integration level between the markets can be evaluated; moreover the results can be compared across different pairs.
For all estimations, the Eicker-White heteroskedasticity robust standard errors are reported in brackets, and the lag order has been fixed at one. In the TVECM the cointegrating vector is the threshold variable that determines the switch from the non-

adjustment regime to the cointegrated one and viceversa. The inaction corridor is defined symmetrically and spans between $-\gamma$ and $+\gamma$. In practice, it is likely that country A's investors undertake cross-border forward trading with country B only when the ratio beetween the two (weighted) prices is large enough to exceed the differences in risks.[8] Formally, let F_A and F_B be the two forward prices, $|log\left(F_A/F_B^{\beta}\right)| \leq \gamma$ defines region 1 (neutral state), and $|log\left(F_A/F_B^{\beta}\right)| > \gamma$ the other one. So one gets that the inaction region is defined as:

$$
\begin{aligned}
F_A/F_B^{\beta} &\geq \exp(-\gamma)\text{if}log\left(F_A/F_B^{\beta}\right) < 0 \\
F_A/F_B^{\beta} &\leq \exp(\gamma)\text{if}log\left(F_A/F_B^{\beta}\right) > 0 \qquad (14) \\
& \qquad (15)
\end{aligned}
$$

For the threshold models, the two dimensional grid search is performed as described above and the number of grid points for both, β and γ, parameters is set to 300. The non linear estimates of the cointegrating and the threshold coefficients, $(\hat{\beta}, \hat{\gamma})$ are obtained by minimizing the Negative Log-likelihood. For all estimated model, in Figure 6 in the Appendix the equilibrium terms are reported by splitting data points in regime 1 and in regime 2.

5.1 The UK -France

Electricity forward contracts are traded in the financial markets and generally do not imply physical exchanges. Nevertheless, cross-border hedging strategies are linked to the possibility of physical exchanges of energy. The existence of a direct interconnection between the British and French power markets, coupled with coordination mechanisms between the two countries, matters for the results. Table 4 reports the estimates of the models.

The estimate of the threshold is $\hat{\gamma} = .351$ (i.e. $.704$ and 1.420 define the bounds for the ratio of the weighted prices). The estimated cointegrated coefficients are $\tilde{\beta} = 1.158$ and $\hat{\beta} = 1.059$ for the VECM and TVECM, respectively. The latter value is numerically close

[8] For a more complete description of cross-hedging of electricity see among others Woo et al. (2001).

	$VECM$	$TVECM$	
β	1.158 (0.076)	1.059	
γ		0.351	
		$REGIME1$ 90.5prc	$REGIME2$ 9.5prc
	Equation1		
λ	-0.045 (0.013)	-0.024 (0.014)	-0.141 (0.041)
μ	-0.023 (0.007)	-0.001 (0.002)	-0.057 (0.020)
$\delta1$	0.053 (0.047)	0.037 (0.056)	0.198 (0.066)
$\delta2$	0.004 (0.031)	0.020 (0.034)	-0.012 (0.074)
	Equation2		
λ	0.075 (0.019)	0.054 (0.018)	0.067 (0.043)
μ	0.037 (0.009)	0.009 (0.003)	-0.022 (0.017)
$\delta1$	0.101 (0.039)	0.069 (0.037)	0.267 (0.113)
$\delta2$	-0.019 (0.036)	-0.029 (0.032)	0.096 (0.140)
W_{Dyn}		7.230 [.124]	
W_{ECM}		8.861 [.012]	
$NLogL$	-4916.009	-4938.312	
AIC	-4900.009	-4906.312	
BIC	-4892.246	-4890.786	

Table 4: **U-F estimates**; the Eicker - White S.E. are reported in round brackets; p-values for the Wald tests are in square brackets

to 1. Whether $\tilde{\beta}$ significantly differs from 1 can be tested (Johansen, 1995). The equilibrium term is inside the bounds the 91% of times, and outside the 'non-adjustment' corridor in the remaining 9% of cases. These percentages are expected as the prices difference should be virtually null in absence of events s.a. relevant maintenance operations or new regulated prices in a market. How the observations switch from one regime to the other (due to the equilibrium relationship in absolute values being below or above $\hat{\gamma}$) is shown in Figure 6. Outside the bounds the adjustment coefficient of the first equation (UK) is significant. In the remaining cases the loadings are insignificant or numerically very small. Indeed, the wald test for the equality of adjustment coefficients rejects the null. The Wald test for the dynamic component is insignificant.

5.2 Germany - The Netherlands

As UK and France, Germany and the Netherlands belong to a common regional initiative, which in their case is the CWE MC. The results for the latter couple of (log-)prices are reported in Table 5.

The estimated threshold value is $\hat{\gamma} = .248$ (i.e. $.780$ and 1.281 are the bounds for $F_{GE}/F_{NE}^{\hat{\beta}}$), which is lower than the .35 estimated in case of UK and France. This seems to reflect a higher level of interconnection between Germany and the Netherlands than the UK- France. The estimated cointegrating vector is $\hat{\beta} = .968$, and in the linear case, $\tilde{\beta}$=.944. Similar to the UK - France case, over the 94% of times the two prices are close, while in the remaining 5% of cases the error toward the equilibrium exceeds the bounds. The adjustment coefficients are either small or non significant in Regime 1. In the second regime the loading of the Nederlands equation gets larger. Strangely one dymanic parameter of the first equation becomes very large. This figure needs to be taken with caution as the dymanic part of the TVECM may be imprecisely estimated, because of the small number of observations in the second regime.

5.3 Germany - France

Germany and France belong to the CWE MC and are well interconnected markets with volumes of exchanges between these platforms that lead to significant links between the two markets. Table **G-F** reports the estimates.

The point estimates of the cointegrating coefficients are $\tilde{\beta} = .887$ (which is not statistically different from 1) in case of the linear model, and $\hat{\beta} = .981$ for the threshold one. The threshold $\hat{\gamma} = .244$ is numerically close to the one estimated for the Germany - Netherlands case and $\exp(\pm\hat{\gamma}) = .7831$ and 1.276. Non-adjustment state dominates

	$VECM$	$TVECM$	
β	0.944 (0.032)	0.968	
γ		0.248	
		$REGIME1$ 94.85prc	$REGIME2$ 5.1prc
	Equation1		
λ	-0.085 (0.049)	-0.045 (0.076)	-0.001 (0.043)
μ	0.016 (0.010)	0.007 (0.008)	-0.041 (0.017)
$\delta 1$	0.003 (0.056)	0.122 (0.048)	-0.134 (0.093)
$\delta 2$	0.042 (0.044)	0.003 (0.042)	-14.362 (2.446)
	Equation2		
λ	0.290 (0.086)	0.135 (0.036)	0.534 (0.101)
μ	-0.052 (0.016)	-0.010 (0.004)	-0.084 (0.025)
$\delta 1$	-0.096 (0.081)	0.132 (0.050)	-0.502 (0.142)
$\delta 2$	0.014 (0.043)	-0.033 (0.031)	1.980 (1.983)
W_{Dyn}		104.725 [.000]	
W_{Dyn}		13.948 [.001]	
NLogL	-2647.111	-2702.121	
AIC	-2631.046	-2670.121	
BIC	-2625.617	-2625.618	

Table 5: **G-N estimates**; the Eicker - White S.E. are reported in round brackets; p-values for the Wald tests are in square brackets

the pooled data set ($|z_{t-1}| \leq \hat{\gamma}$ 95 % of times). In the first regime the loading of the France equation is significant. In contrast, in regime 2 only Germany appears to adjust toward the equilibrium. Moreover in that regime the loading of the second equation, although not signficant at the 5% level, is negative. I would have expected it to be positive. When $log(F_{GE}) - \beta log(F_{FR})$ is large one would expect F_{FR} to rise. By omitting the threshold and estimating a VECM the loadings are not significant.

	$VECM$	$TVECM$	
β	0.887 (0.057)	0.982	
γ		0.244	
		$REGIME1$ 94.99prc	$REGIME2$ 5.02prc
	Equation 1		
λ	-0.103 (0.071)	0.023 (0.044)	-0.641 (0.181)
μ	0.041 (0.030)	0.001 (0.003)	-0.165 (0.047)
$\delta 1$	-0.086 (0.077)	0.024 (0.061)	0.528 (0.299)
$\delta 2$	0.139 (0.077)	0.119 (0.073)	-0.577 (0.298)
	Equation 2		
λ	0.046 (0.062)	0.117 (0.048)	-0.235 (0.148)
μ	-0.018 (0.003)	-0.003 (0.003)	-0.053 (0.047)
$\delta 1$	0.160 (0.082)	0.087 (0.052)	0.722 (0.291)
$\delta 2$	-0.031 (0.073)	0.087 (0.054)	-0.705 (0.293)
W_{Dyn}		14.478 [.006]	
W_{ECM}		15.673 [.000]	
NLogL	-2737.046	-2782.333	
AIC	-2721.046	-2750.333	
BIC	-2715.461	-2739.163	

Table 6: **G-F estimates**; the Eicker - White S.E. are reported in round brackets; p-values for the Wald tests are in square brackets

5.4 The UK - The Netherlands

The value $\tilde{\beta}$ is significantly larger than 1, and $\hat{\beta}$=1.30. The estimated threshold is $\hat{\gamma} = .988$, which is mutch larger than estimated threshold for the previous pairs of prices. Despite the large threshold, the first regime holds 24% of times only. In regime 1, point estimates of the loading and the constant term of the first equation are strangely large, while they are insignificant for the second equation. In the second regime loadings and intercepts are significant but small. The Wald statistics suggest significant differences

	$VECM$	$TVECM$	
β	1.221 (0.084)	1.300	
γ		.988	
		$REGIME1$ 23.62prc	$REGIME2$ 76.38prc
	Equation1		
λ	-0.058 (0.017)	-0.392 (0.102)	-0.053 (0.018)
μ	-0.049 (0.015)	-0.360 (0.094)	-0.064 (0.022)
$\delta 1$	0.074 (0.049)	0.244 (0.090)	0.034 (0.057)
$\delta 2$	0.013 (0.040)	-0.137 (0.099)	0.047 (0.037)
	Equation2		
λ	0.070 (0.019)	0.077 (0.060)	0.098 (0.030)
μ	0.059 (0.015)	0.077 (0.055)	0.116 (0.036)
$\delta 1$	0.082 (0.052)	0.083 (0.042)	0.079 (0.077)
$\delta 2$	-0.053 (0.063)	-0.343 (0.135)	0.049 (0.036)
W_{Dyn}		11.553 [.021]	
W_{ECM}		11.178 [.003]	
NLogL	-4037.665	-4065.967	
AIC	-4021.665	-4033.967	
BIC	-4014.610	-4019.855	

Table 7: **U-N estimates**;the Eicker - White S.E. are reported in round brackets; p-values for the Wald tests are in square brackets

between the coefficients in the two states.

5.5 The Netherlands - France

In this case, the estimated γ is very small, which may be what leads the first state to hold 7% of times. Moreover, loadings estimates suggest that the adjustment toward the equilibrium applies only inside the bounds, which contrasts with the expectations.

	$VECM$	$TVECM$	
β	0.913 (0.058)	0.957	
γ		0.074	
		$REGIME1$ 7.174 prc	$REGIME2$ 92.82prc
	Equation1		
λ	-0.080 (0.024)	-0.107 (0.200)	-0.068 (0.026)
μ	0.032 (0.010)	0.019 (0.010)	0.014 (0.006)
$\delta 1$	-0.032 (0.029)	-0.029 (0.062)	-0.054 (0.033)
$\delta 2$	0.120 (0.039)	0.453 (0.111)	0.089 (0.041)
	Equation2		
λ	0.069 (0.023)	1.351 (0.566)	0.051 (0.021)
μ	-0.028 (0.010)	-0.072 (0.029)	-0.011 (0.006)
$\delta 1$	0.007 (0.048)	0.008 (0.212)	0.010 (0.040)
$\delta 2$	-0.010 (0.038)	0.265 (0.236)	-0.020 (0.033)
W_{Dyn}		13.516 [.009]	
W_{ECM}		7.108 [.028]	
NLogL	-4742.967	-4771.906	
AIC	-4726.967	-4739.906	
BIC	-4729.309	-4724.592	

Table 8: **N-F estimates**; the Eicker - White S.E. are reported in round brackets; p-values for the Wald tests are in square brackets

5.6 The UK - Germany

For these two markets, the estimated γ is big and $\tilde{\beta}$ and $\hat{\beta}$ are far from one. In regime 1 the loadings and the intercepts of the second equation are significant but the point estimates are very small. In the second regime the adjustment is not significant in case of the UK equations while it is significant and big for Germany. Wald tests do not evidence asymmetries neither in the dynamic nor in the error correction coefficients.

	$VECM$	$TVECM$	
β	1.350 (.093)	1.252	
γ		1.049	
		$REGIME1$ 93.62prc	$REGIME2$ 6.38prc
	Equation1		
λ	-0.040 (0.015)	-0.022 (0.017)	0.129 (0.132)
μ	-0.049 (0.018)	-0.020 (0.014)	0.201 (0.166)
$\delta 1$	-0.002 (0.014)	-0.009 (0.015)	0.011 (0.324)
$\delta 2$	0.038 (0.041)	0.070 (0.054)	-0.046 (0.074)
	Equation2		
λ	0.095 (0.029)	0.072 (0.034)	0.433 (0.203)
μ	0.114 (0.034)	0.061 (0.027)	0.460 (0.234)
$\delta 1$	0.064 (0.049)	0.034 (0.046)	1.364 (0.856)
$\delta 2$	0.023 (0.051)	0.081 (0.041)	-0.035 (0.165)
W_{Dyn}		6.472 [.167]	
W_{ECM}		4.107 [.128]	
NLogL	-2752.992	-2775.507	
AIC	-2736.992	-2743.507	
BIC	-2731.499	-2732.520	

Table 9: **U-G estimates**; the Eicker - White S.E. are reported in round brackets; p-values for the Wald tests are in square brackets

Overall the estimated models appear to be appropriate for capturing the integration across EU prices and the possible non-linearities in the adjustment process. Results found using the threshold models suggest that week ahead forward markets are more integrated in case the considered markets are neighbouring markets. When compared based on the AIC and the BIC, the threshodl model exibits a better performance than the VECM for all the considered pairs of prices.

6 Testing for threshold

The hypothesis of linear VECM against the threshold one is tested using the multivariate supLM statistic of Hansen and Seo (2002) as above described.
The results of the test statistics are reported in the table 10 that follows. The empirical

	UK-FR	GE-NE	GE-FR	UK-NE	NE-FR	UK-GE
$supLM$	17.470	15.537	18.755	18.296	22.289	16.851
$crit-val$	21.197	19.280	19.462	20.556	21.233	18.054
$p-val$	.191	.235	.065	.114	.034	.082

Table 10: **supLM**

distribution of the statistic is obtained by residual bootstrap, and the number of simulations is set to 5000. The figures show that the supLM statistic is significant at the 10% level only for Germany - France, The Netherlands - France and The Uk - Germany pairs of prices.

7 Robustness of the results: evidence from the MM model

In this section, it is verified whether the evidence found through Hansen and Seo's model is consistent with the results of an alternative approach, Granger and Hyung's LinMM model, which considers explicitly the minimizing and maximizing behaviors of economic agents. Moreover, I modify the specification proposed by the authors to take into account the opposite minimizing and maximizing behaviors that the agents will show when the equilibrium is positive or negative. The model is defined in (13) with $z_t = x_t - \beta y_t$, but with β estimated instead of being fixed at one[9]. Coherently with

[9]The two-step approach of Engle and Granger is used for estimating β. Note that the estimated equilibrium terms differ from those obtained in the TVECM case by ML.

this framework, in case of positive z_t the system gives rise to two regions:

- RIp. z_{t+1} is a RW with drift $a^+ - d^+$ if $z_t < b^+ - a^+$ and

- RIIp. z_{t+1} is stationary if $z_t > b^+ - a^+$.

For negative z_t, two other regions arise:

- RIn. z_{t+1} is a RW with drift $a^- - d^-$ if $z_t > b^- - a^-$ and

- RIIn. z_{t+1} is $I(0)$ if $z_t < b^- - a^-$.

Overall, the system gives rise to an inaction band for small (weighted) differences between prices inside an upper and a lower cointegrated regions. Differently from the estimated TVECM, the LinMM is specified in such a way to allow for the thresholds and drifts to vary when the equilibrium term is positive or negative. Tables 11-16 summarize the estimates of the long-run coefficients for all pairs of prices.

	linMMmodel	
	$z_t > 0$	$z_t \leq 0$
	$z_t > b - a$ .9%	$z_t < b - a$ .4%
a	-0.004 (0.003)	0.004 (0.003)
b	0.677 (0.050)	-0.727 (0.073)
d	0.013 (0.003)	-0.011 (0.003)
NLogL	-4908.577	
AIC	-4897.577	
BIC	-4896.367	

Table 11: **Linearized MM model estimates - UF**

The evidence found shows that the drift terms, $a^+ - d^+$ $(a^- - d^-)$,in general are close to zero but negative (positive) in case $z_t > 0$ $(z_t < 0)$. This implies that if z_t is in the

	linMMmodel	
	$z_t > 0$	$z_t \leq 0$
	$z_t > b - a$ 2.2%	$z_t < b - a$ .0%
a	0.010 (0.005)	0.000 (0.006)
b	0.348 (0.039)	-0.964 (0.334)
d	0.011 (0.002)	-0.016 (0.003)
NLogL	-2603.229	
AIC	-2592.229	
BIC	-2591.019	

Table 12: **Linearized MM model estimates - GN**

	linMMmodel	
	$z_t > 0$	$z_t \leq 0$
	$z_t > b - a$ 2.2%	$z_t < b - a$ 1.1%
a	0.023 (0.008)	-0.007 (0.009)
b	0.235 (0.033)	-0.416 (0.065)
d	0.005 (0.002)	-0.009 (0.004)
NLogL	-2767.100	
AIC	-2756.100	
BIC	-2754.889	

Table 13: **Linearized MM model estimates - GF**

neutral state it tends to stay there unless the error term is sufficiently large to bring the process outside the bounds. Indeed, the percentages of observations in the cointegrated regimes (i.e. such that $z_t > b - a$ in case z_t is positive and $z_t < b - a$ for negative z_t) are much lower than those estimated through the previous model.
The figures reported in Tables 11 - 16 support the assumption of symmetric thresholds (b-a) for UK-FR and NE-FR pairs. Point estimates of the bound for $z_t > 0$ in case of GE-NE and GE-FR are close to TVECM estimates. For UK-NE and UK-GE point estimates

	linMMmodel	
	$z_t > 0$	$z_t \leq 0$
	$z_t > b - a$ 2.6%	$z_t < b - a$ .0%
a	0.002 (0.004)	-0.063 (0.026)
b	0.507 (0.031)	-2.895 (0.370)
d	0.005 (0.002)	-0.009 (0.003)
NLogL	-4044.501	
AIC	-4033.501	
BIC	-4032.290	

Table 14: **Linearized MM model estimates - UN**

	linMMmodel	
	$z_t > 0$	$z_t \leq 0$
	$z_t > b - a$ 1%	$z_t < b - a$ .4%
a	-0.006 (0.003)	0.003 (0.003)
b	0.738 (0.053)	-0.648 (0.050)
d	0.007 (0.002)	-0.006 (0.003)
NLogL	-4731.530	
AIC	-4720.530	
BIC	-4719.320	

Table 15: **Linearized MM model estimates - NF**

of b in the positive and negative cases, respectively, are very large. These may be imprecise estimates and reflect problems of convergence. Overall, results of the Lin MM model suggest the existence of a neutral regime. However, based on model's estimates, cointegration is rarely active.

	linMMmodel	
	$z_t > 0$	$z_t \leq 0$
	$z_t > b - a$ .0%	$z_t < b - a$ .0%
a	0.004 (0.019)	0.001 (0.003)
b	3.389 (0.466)	-0.577 (0.072)
d	0.012 (0.004)	-0.009 (0.004)
NLogL	-2742.931	
AIC	-2731.931	
BIC	-2730.720	

Table 16: **Linearized MM model estimates - UG**

8 Conclusion

In this paper I have proposed to use bivariate TVECMs for analysing the convergences in pairs of forward prices across British, German, Dutch and French electricity markets. The use of threshold models is motivated by the expectation that adjustments toward the equilibrium may operate only when the (weighted) spreads in prices exceed risks associated with different hedging strategies. When the domestic market of one country is affected by some shocks (e.g. unforeseen plants' stops or new regulations being approved), the prices may depart from the equilibrium level. This deviations may make it convenient investing in cross-border forward contracts (in general coupled with investments in hedging instruments against the variability of transportation costs). This practice can induce interdependencies in prices and adjustment mechanisms. From the empirical analysis using TVECMs à la Hansen and Seo it appears that conditioning on the absolute values of the errors toward the equilibrium helps to capture the dynamics of cross-border forward trading, and it contributes to examine price convergences appropriately. Out of the six couples of prices analysed, the estimates support the theoretical assumption in four cases, i.e. for the dynamics of the UK - France, Germany - the Netherlands, Germany - France and the UK - Germany prices. However, the SupLM statistic for the existence of a threshold is significant in three cases only, namely Germany - France, the Netherlands - France and the UK - Germany. The evidence found using the LinMM model of Granger and Hyung confirms the existence of a band of non-adjustment. In fact, the percentages of data points in the cointegrated regimes are much smaller than for the TVECM (and null in one out of six cases), which suggests that cointegration is rarely active. When compared based on the Akaike Information Criteria, TVECMs perform better than the VECMs and the LinMMs in all but the Germany - France case. For further research I would like to allow for asymmetric thresholds also in case of TVECMs, and for the chance that the thresholds vary over the seasons.

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9 Appendix

9.1 Small sample performance

Monte Carlo simulation experiments are performed to verify the convergence of algorithms for the TVECM and the LinMM model for $n = 250$ and 1000 replications.

9.1.1 Small sample performance of TVECM

The data generating process is:

equation $$\Delta x_t = \begin{pmatrix} -.2 \\ +.3 \end{pmatrix} (x_{1,t} - \beta_0 x_{2,t}) \, 1 \, (x_{1,t} - \beta_0 x_{2,t} > \gamma_0) + e_t$$

with e_t i.i.d. Normal$(0, I_2)$. The cointegrating coefficient, β_0, and the threshold value, γ_0, are set at 1. The results are reported in Table 17. The results show that β has

n=250	MEAN	RMSE	MAE	Percentiles				
				5	25	50	75	95
$\beta - \beta_0$	.003	.058	.039	-0.088	-0.023	0.001	0.029	0.102
$\gamma - \gamma_0$	-.117	.790	.610	-1.000	-0.775	-0.319	0.197	1.689

Table 17: **Distribution of estimators** - The estimators $\hat{\beta}$ and $\hat{\gamma}$ are unrestricted estimators obtained as described in Section 2.

an approximately symmetric and unbiased distribution; in contrast, the estimator of γ has an asymmetric and quite inaccurate distribution. Overall the results confirm convergence of the algorithm.

9.1.2 Small sample performance of LinMM model

To simulate a Lin MM model the following process is generated:

$$\begin{aligned}\Delta x_{1,t+1} &= min(.02, -z_t + .6) - .06\Delta x_{1,t} + .2x_{2,t}1(z_t > 0) + \\ &\quad +max(-.2, -z_t - .9) - .02\Delta x_{1,t} + .04\Delta x_{2,t} + u_{1,t+1} \\ \Delta x_{2,t+1} &= .02 + u_{2,t+1} \end{aligned} \quad (16)$$

Table 18 reports simulations results. The estimators tend to converge to the true values

n=250	MEAN	RMSE	MAE	Percentiles				
				5	25	50	75	95
$x_{1,t} - x_{2,t} > 0$								
$a^+ - a_0^+$	0.037	0.190	0.150	-0.259	-0.085	0.027	0.159	0.367
$b^+ - b_0^+$	0.010	0.171	0.171	-0.264	-0.108	0.006	0.123	0.287
$d^+ - d_0^+$	0.002	0.127	0.101	-0.210	-0.083	-0.001	0.091	0.211
$x_{1,t} - x_{2,t} \leq 0$								
$a^- - a_0^-$	-0.024	0.172	0.134	-0.316	-0.130	-0.014	0.089	0.244
$b^- - b_0^-$	-0.009	0.134	0.105	-0.228	-0.099	-0.012	0.077	0.206
$d^- - d_0^-$	0.002	0.097	0.077	-0.163	-0.062	0.003	0.065	0.164

Table 18: **Distribution of estimators** - The estimators are obtained by setting the cointegrating coefficient at -1.

but their distributions are quite dispersed.

9.2 Stability analysis

To ascertain that estimation results are not specific of the considered samples, recursive estimation of the coefficients is performed. Estimates are found to be stable over time. The estimated loadings in regime 1 and regime 2 for the UK and GE pair are reported in Figure 2.[10]

[10]The remaining cases are not reported for the sake of space and are available upon request.

	UK-FR	GE-NE	GE-FR	UK-NE	NE-FR	UK-GE
$ARCH(5)$-E	-*	*-	**	**	**	-*
$ARCH(5)$-E1	-*	**	–	–	–	-*
$ARCH(5)$-E2	–	–	–	-*	-*	–

Table 19: **Heteroscedasticity**

9.3 Heteroskedasticity analysis

A visual inspection of Figure 3 suggests that data series are characterized by volatility varying over time. It is interesting to analyse whether different levels of volatility are associated with different regimes. If so by estimating separately the variances for each regime, ARCH effects should decrease[11]. Consider the TVECM in (4) and let e_1 and e_2 be the estimated residuals corresponding to the two regimes.

Table 19 summarizes the results. In all cases, resides of linear VECM exhibit ARCH(5) effects in at least one equation. For the GE-FR pair ARCH(5) effects disappear by splitting the regimes. For the remaining pairs, evidence of autoregressive heteroscedasticity is found in the "standard" state (regime 1 in case of GE-NE and UK-GE, and regime 2 for UK-NE and NE-FR). These findings suggest two considerations: i) ARCH effects may disappear from the 'extreme' regime because a few observations are found in this regime; ii) observations that follow in regime 2 are concentrated in a short time frame (see Figure 6).

[11]This does not affects coefficients estimates since a ML estimates under assumption that resides are i.i.d. have been performed

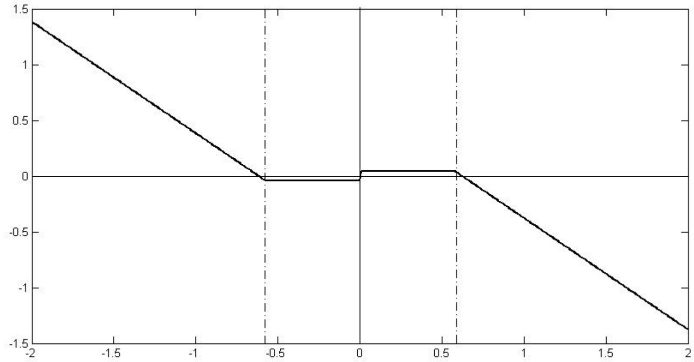
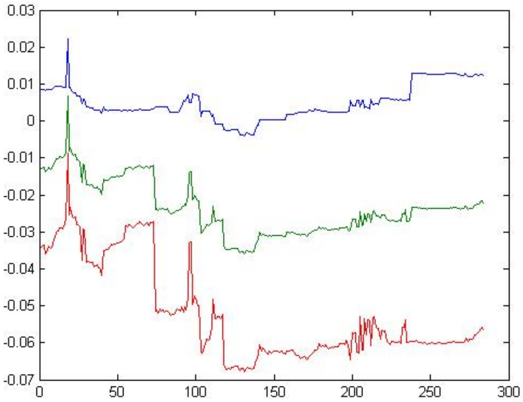
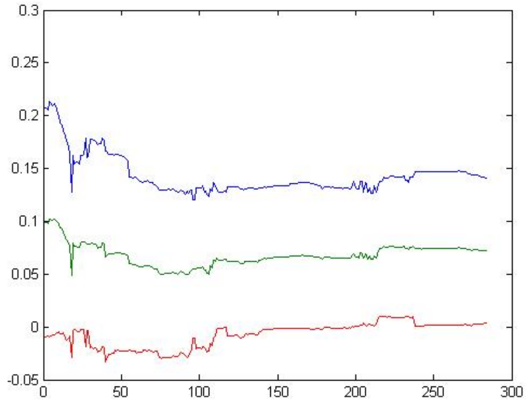


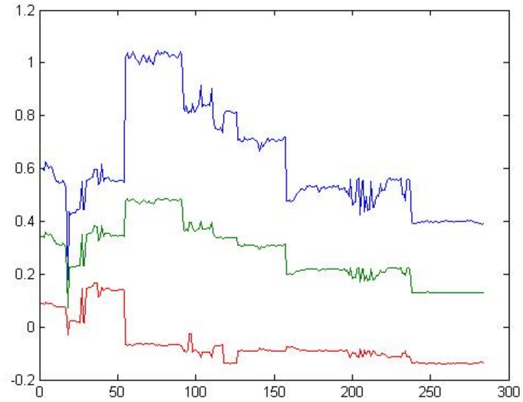
Figure 1: Δz_{t+1} on z_t with $(a^+, b^+, d^+; a^-, b^-, d^-) = (.02, .6, -.02; -.02, -.6, .02)$



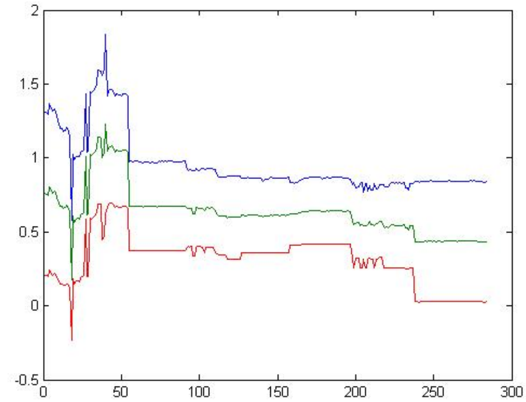
(a) Equation1 Regime1



(b) Equation2 Regime1

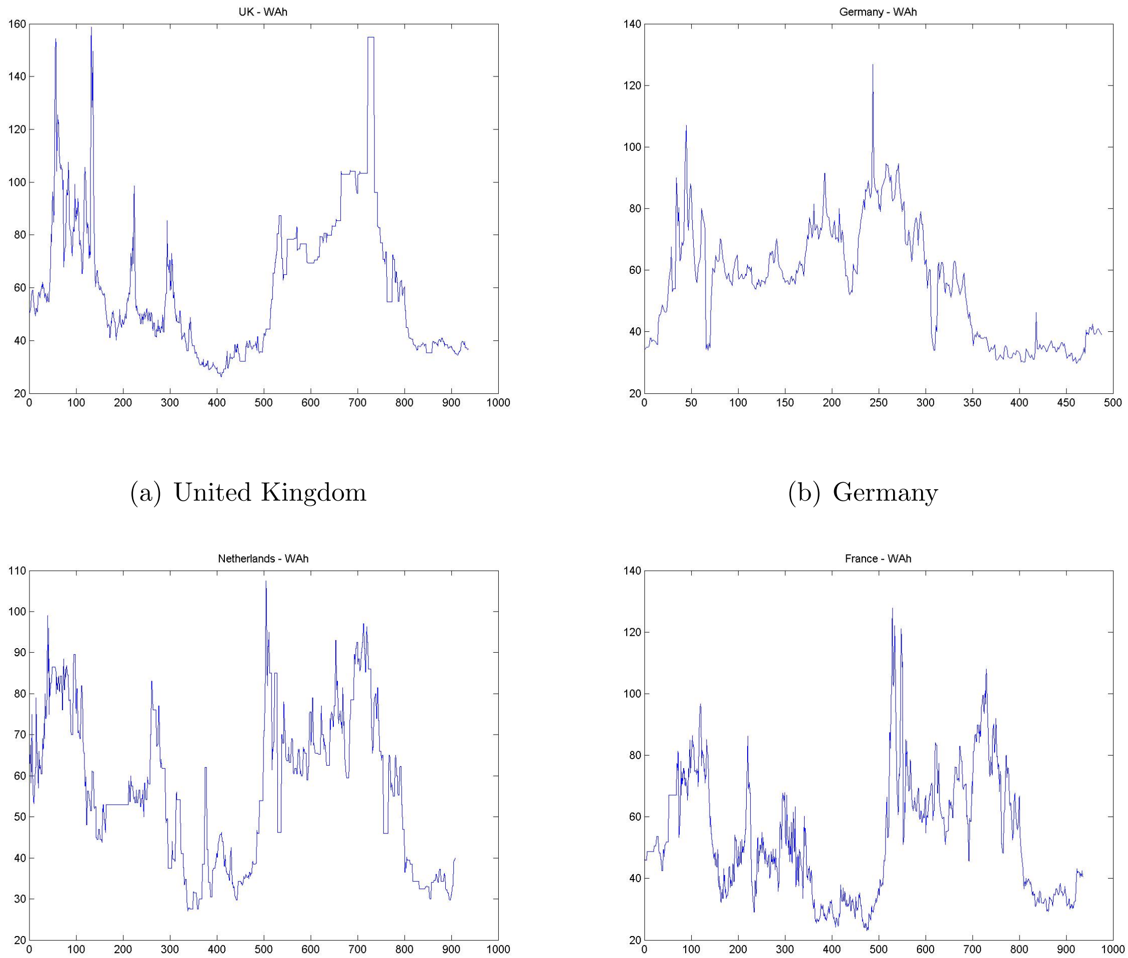


(c) Equation1 Regime2



(d) Equation2 Regime2

Figure 2: Recursive coefficients estimates - UK-GE pair



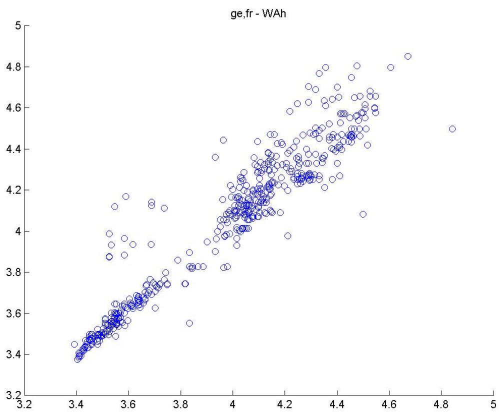
(a) United Kingdom

(b) Germany

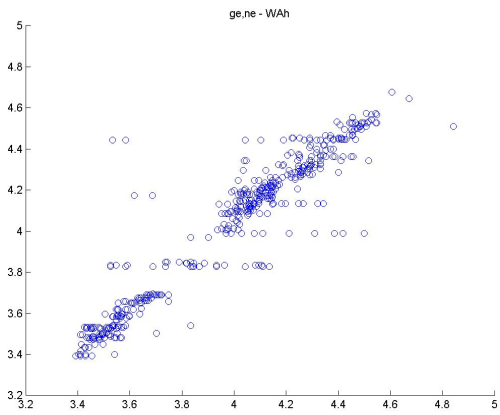
(c) Netherlands

(d) France

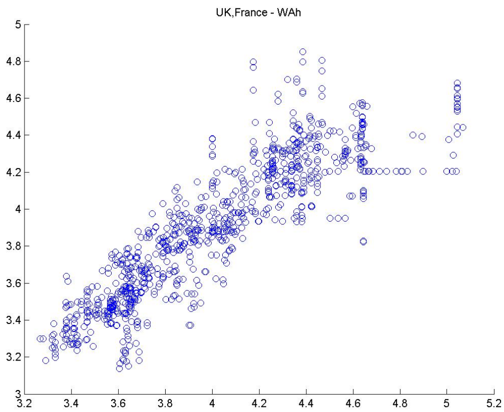
Figure 3: Week ahead baseload electricity prices



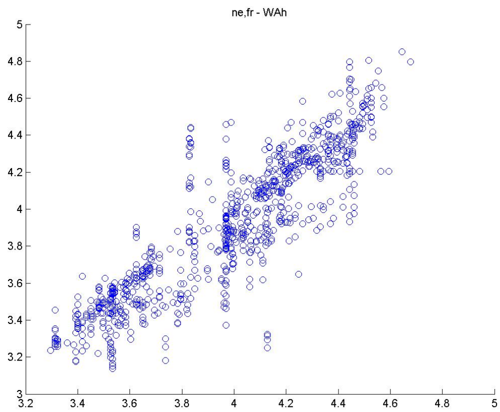
(a) Germany - France, 2007.9 - 2009.9



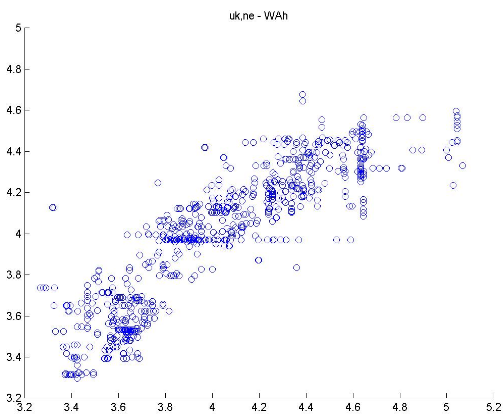
(b) Germany - Netherlands, 2007.9 - 2009.9



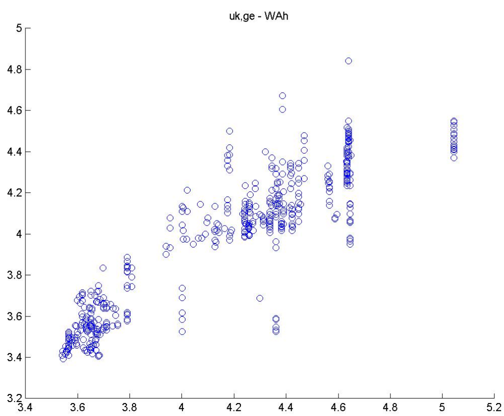
(c) United Kingdom - France, 2005.6 - 2009.9



(d) Netherlands - France, 2005.6 - 2009.9

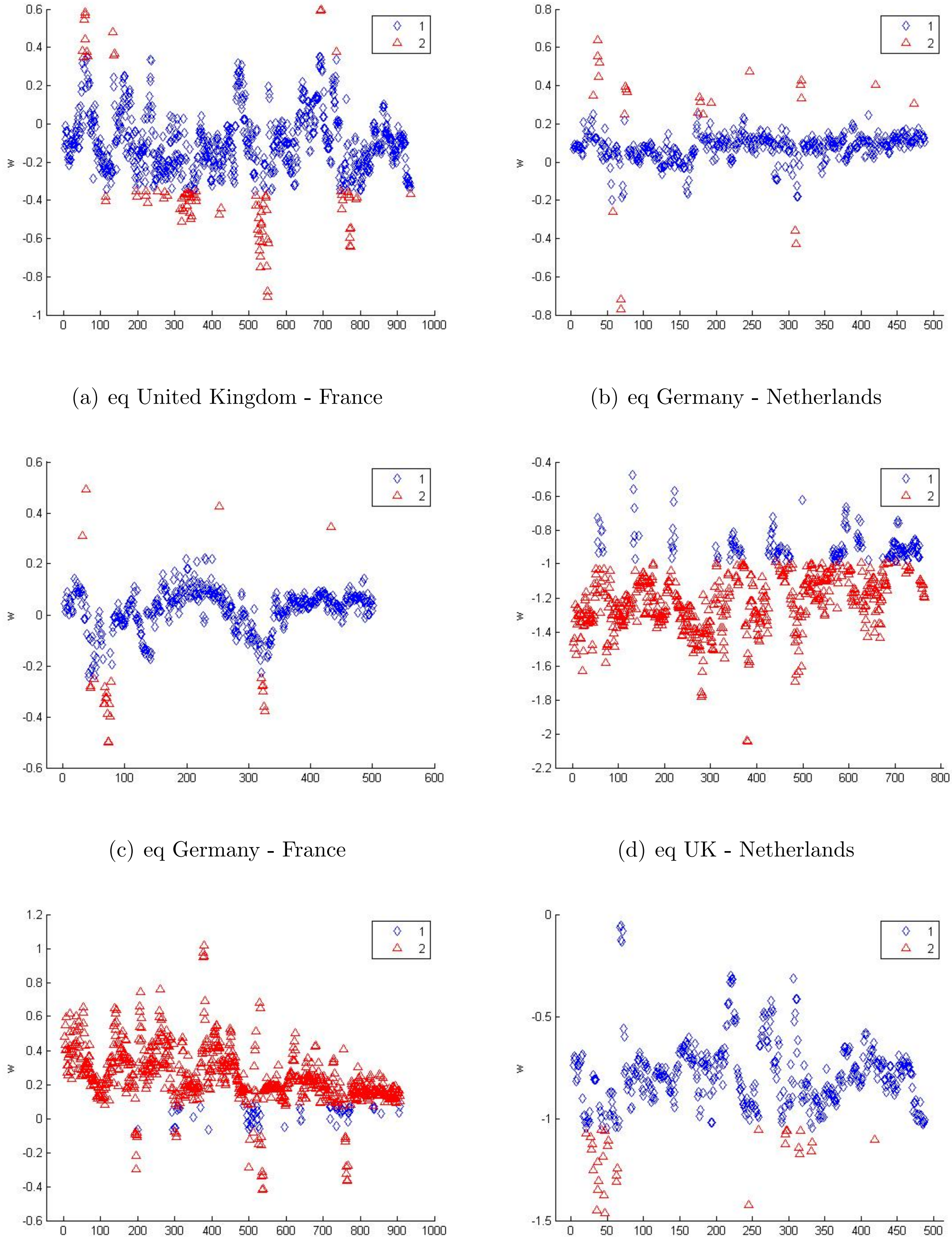


(e) United Kingdom - Netherlands, 2005.6 - 2009.9



(f) United Kingdom - Germany, 2007.9 - 2009.9

Figure 4: Scatter Plots of series



(a) eq United Kingdom - France

(b) eq Germany - Netherlands

(c) eq Germany - France

(d) eq UK - Netherlands

(e) eq Netherlands - France

(f) eq UK - Germany

Figure 5: Equilibrium term by regime