Germany´s Energy Transition and its Potential Effect on European Electricity Spot Markets

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ABSTRACT

Germany´s *Energiewende* (energy transition) called for the closure of all of its nuclear plants by 2022 and has ambitious targets for renewable energy sources (RES-E). This transition is so far unique in a major industrial country and its viability has been subject of debate. Since a pan European electricity market is envisaged for the near future, this paper examines the potential impact of the German energy transition on the integration of European electricity markets. First, a time varying long memory analysis is conducted to identify any change in mean reversion then the potential impact of RES-E-generated electricity produced in Germany on other European electricity markets is assessed, by employing MGARCH (multivariate generalized autoregressive conditional heteroscedasticity) models with constant and time-varying correlations. The short and long run interrelationship of daily electricity spot prices of APX-ENDEX (UK and Netherlands), Belpex (Belgium), EPEX-DE (Germany and Switzerland), OMEL (Spain and Portugal), Nord Pool (Finland, Denmark and Norway) and EPEX-FR (France) with wind penetration introduced by the German system is studied from November 2009 to October 2012, thus covering the period before and after the closure of eight nuclear power plants. There are indications of positive cross-market and lagged spillovers, as well as a significant reduction in electricity spot prices with increasing wind penetration. Positive time-varying correlations between spot market volatilities are found in markets with substantial shared interconnector capacity. Wind penetration volatility is negatively associated with electricity spot price fluctuations. Evidence is also provided that after Germany´s energy transition, convergence in liberalized EU electricity markets has decreased.

Keywords: electricity market integration, energy transition, volatility transmission, long memory

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1. Introduction

The promotion of renewable energies in Germany was first legislated by the Renewable Energy Source Act (RESA, 1991) in 1991. Since then, renewable electricity generation has grown considerably. Installed wind-power capacity in Germany has increased from 183MWh in 1992 to 29.060MWh in 2011, which corresponds to over 30% of the total wind power capacity installed in Europe (BWE, 2012). The *Energiekonzept* (Energy Concept) - the long term energy strategy promoting this development - was proposed in 2010 aiming at making Germany one of the most energy-efficient and environmentally friendly economies (Bundesregierung, 2011). One year later, this strategy was reinforced as a reaction to the multiple reactor meltdowns in Fukushima. The accident led to a broad consensus within the German government in favour of the implementation of the *Atomausstiegsgestz* (Nuclear Phase-Out Act), by closing eight nuclear power plants. In parallel, the German government emphasized its commitment to existing RES-E plans, with the Renewable Energy Source Act 2012 (RESA 2012). This aims to increase electricity generated from RES-E to at least 35% by 2020 and to a minimum of 80% by 2050 (RESA, 2012). RESA 2012 reaffirmed the basic principles of the feed-in tariff policy, which prioritizes renewable energy sources, pledges to connect all renewable producers to the grid and guarantees a favourable unit price. Pursuing a nuclear phase-out together with ambitious renewable energy targets, is so far unique for a major industrial country with a low hydro share of its electricity. In fact, the German Environment Minister, Peter Altmaier, recently admitted that his country had taken a unilateral course in 2011: "It was not possible to discuss the consequences of such a decision with Germany's neighbours. Now is the time for that" (European Energy Review, 2012). A consensus within European energy policy could promote energy mixes, making maximum use of complementarities and leading to dynamic pricing. It is understood that diverse resource endowments and generating technologies across integrated systems offer greater resilience and a more economics-based response to shocks in electricity markets. In contrast, if all markets were to focus on their own needs, their combined electricity system could result in an over-investment in capacity: a centrally coordinated dispatch over a larger region requires a lower reserve margin on a national level and thus has the potential to increase efficiency (Hooper and Medvedev, 2009). A paradigm example of such complementarity is the flow in the NorNed interconnector cable, which changes direction depending on precipitation levels. According to ENTSO-E (European Network of Transmission System Operators for Electricity) electricity exchange statistics, the Netherlands was a net-importer from Norway in both 2008 (2.8 TWh) and 2009 (1.6 TWh). Yet in 2010, which was a very dry year in Scandinavia, the Netherlands became a net exporter to Norway (1.0 TWh). This resulted in lower average prices with fewer fluctuations in both electricity markets (Teusch, 2012).

This paper aims to contribute to the ongoing debate on the integration of European electricity markets and Germany´s energy policy, by empirically investigating the interrelationships of European electricity spots prices as well as the potential impact of an increased share of RES-E on the European system.

2. Literature

Studies such as Gross et al. (2006), Holttinen et al. (2009) and Smith et al. (2007) have highlighted the challenges associated with increased RES-E penetration. There is, for example, a significant risk that a system with high wind power capacity will face shortages of electricity. Other studies (e.g., Bode and Groscurth, 2006; Gil et al., 2012; Jacobsen and Zvingilaite, 2010; Neubarth et al., 2006; Saenz de Miera et al., 2008; Sensfuß et al., 2008) have shown that electricity spot market prices decrease to varying extents with the in-feed of wind-generated electricity. This reduction in prices is generally attributed to cheaper wind-generated electricity superseding offers from generators whose technologies have higher marginal costs (Sensfuß et al., 2008; Woo et al., 2011). Nevertheless, this effect may have the drawback of an overall increase in spot price volatility due to the combined effect of the very limited storability of electricity and the high volatility of wind power (Woo et al., 2011; Milstein and Tishler, 2011; Green and Vasilakos, 2010).

Woo et al. (2011) used quarter-hourly electricity price data and explanatory variables (quarter-hourly nuclear generation and loads, daily Henry Hub gas price, as well as binary indicators to account for seasonal effects) from Texas between January 2007 and May 2010. Via a regression analysis, they inferred that wind generation tends to reduce electricity spot prices but increases their variance. Milstein and Tishler (2011) analysed the relationship between intermittent renewable energy, optimal endogenous generating capacity mix, energy production by technology and market prices as a Cournot market, where the players were Combined Cycle Gas Turbine (CCGT) and Photovoltaic (PV) generation. Their solution to this two-stage game, using real-world Israeli data, shows that rising adoption of PV can increase electricity spot price volatility. Green and Vasilakos (2010) examined the impact of wind generation on British hourly equilibrium prices and output, using data on expected wind generation capacity and demand for 2020. They found that the volatility of prices and of generators' profits increases significantly.

Despite the fact that the integration of electricity markets is a promising instrument when managing intermittent RES-E, previous studies assessing volatility interrelationships among electricity markets have neglected the potential impact of RES-E generation. Indeed, Bosco et al. (2007) noted that '[...] *post-reform European price series have generally been studied in isolation and the issue of the interdependency in the price dynamics of neighbouring markets has largely been ignored.'* (p. 2). To date, few studies have applied a multivariate framework to electricity price volatilities. Worthington et al. (2005) employed MGARCH (multivariate generalized autoregressive conditional heteroscedasticity) models to capture the causes and magnitude of price and volatility spillovers within five Australian electricity spot markets. Their results showed positive lagged mean spillovers in only two markets and no mean spillovers across markets. Yet, there were significant own and cross volatility spill over in nearly all markets. In a similar vein, Higgs (2009) employed one Constant Conditional Correlation (CCC) and two Dynamic Conditional Correlation (DCC) models to the spot prices of four Australian electricity markets from 1999 to 2007. She concluded that the less direct the interconnection between regions, the lower the volatility spillovers between them, suggesting that the key to interaction between electricity markets is geographical proximity and interconnector capacity. Le Pen and Sévi (2010) used daily data from March 2001 to June 2005 and used a VAR-BEKK model and Volatility Impulse Response Functions. They found evidence of return and volatility spillovers in forward electricity markets (German, Dutch and British); their estimated impacts are significant, especially in cases of large shocks and/or rapid decay.

Another relevant stream of literature, for the purpose of this study, has used the Law of One Price as the theoretical foundation to determine whether two geographic regions, in which a well-defined product is traded, comprise a single integrated market, considering transportation and transaction costs. For example, Balaguer (2011) assessed the extent of market integration based on pricing behaviour of Norwegian and Swiss exporters, between 2003 and 2009, and concluded that wholesale electricity markets in Sweden and Denmark were highly integrated but Italy, France and Germany diverged. Bower (2002) studied wholesale electricity prices in fifteen locations in Europe (ten within the Scandinavian countries, one in the UK, one in Spain, one in the Netherlands and two in Germany) . His cointegration analysis identified long-run relationships between Germany, Sweden, Finland and Denmark and between Nord Pool, the UK, Germany and the Netherlands. However, he did not conduct a prior unit root test to assess non-stationarity of the data, thus his conclusions may be unreliable. Indeed, Boisselau (2004), while investigating market integration for France, UK, Spain, Germany, the Netherlands and Nord Pool using hourly prices, found that most electricity price series were stationary, and therefore concluded that the nature of the data did not allow for a cointegration analysis. Bosco (2010), on the other hand, using week-daily mean average prices and testing for non-stationarity, found integration between the German and French markets. Robinson (2008) employed retail data from 1978 to 2003 for ten European countries (Denmark, Finland, France, Germany, Greece, Ireland, Italy, Portugal, Spain, UK) and three different methods for testing convergence, based on which he concluded that electricity prices in these countries converged. Armstrong and Galli (2005) examined four main electricity bourses in the Eurozone (Germany, France, Netherlands and Spain), which had common borders and a similar price setting process, from January 2002 to December 2004 to determine whether prices were converging. They distinguished between weekdays and weekends and found that the average price difference decreased between 2002 and 2004 in almost all cases, and more rapidly in peak periods.

In contrast to previous findings, Zachmann (2008) concluded that by mid 2006, market integration for eleven European countries (Austria, France, Germany, Netherlands, Spain, UK, Poland, Czech Republic, East Denmark, West Denmark and Sweden) had not been attained. Based on a Principal Component Analysis of wholesale electricity prices from 2002 to 2006, he rejected the assumption of full market integration. Electricity spot prices from the different markets, according to his findings, were independent processes. Zachmann's (2008) tests for convergence showed that 18 pairs converged, 18 diverged and 19 were insignificant. Although 93% of the studied market pairs featured significant predictable arbitrage opportunities, 42% were not converging toward arbitrage freeness. Zachmann therefore concluded that European market integration is no "*universal process*".

Bunn and Gianfreda (2010) used causality tests, cointegration and impulse-response techniques and modelled price levels and volatilities. Their findings differ from Zachmann's (2008), as they found evidence of increasing market integration for Germany, France, Spain, the Netherlands and the UK. Integration increased with interconnector capacity and when markets were closer; but, in contrast to Armstrong and Galli (2005), they found more integration at base load than at peak load periods. Yet another study, Kalantzis and Milonas (2010) appears to support Armstrong and Galli's (2005) conclusion, since they found spot price convergence over time to be higher during peak hours across eight electricity wholesale markets in central and western Europe (APX-UK, APX-NL, EPEX-FR, Belpex, EPEX-DE, EXAA, Nord Pool and OMEL). In support of Bunn and Gianfreda's (2010) conclusions, Kalantzis and Milonas (2010) also found that interconnection and geographical distance between countries played a crucial role in price dispersion. A more recent study, Pellini (2012), assesses perfect cointegration for fifteen European markets using a time- varying approach to model prices and their volatilities; her fractional cointegration analysis and MGARCH (Multivariate Generalized Autoregressive Conditional Heteroscedasticity) models estimates led her to conclude that integration of European markets is still a long way to go.[2]

From the above, it is noticeable that despite a few investigations of spill-over effects, the potential implications of increasing RES-E penetration levels on price dynamics across electricity markets have been neglected.

[2] In 2010 22.6TWh (19.1%) of electricity in the Netherlands was produced from solid fuels and 77.4TWh (65.5%) from gas. In Belgium 4.4% equalling 4.2TWh of total electricity is being produced by solid fuels and 33.2TWh (34.9%) by gas (European Commission, 2012).

Studies of the convergence of electricity prices have also disregarded implications of RES-E. Moreover, their findings remain mixed with regards to convergence, and it may be argued that contradictions in the literature result from the methodologies adopted in different studies. Most authors have neglected the potential long memory of electricity spot prices, which is consistent with the volatility clusters that are frequently observed in their time series. In addition, description of whether or how outliers, which follow from the spikes that can be caused by plant failures and special events, were treated in their analyses and therefore we lack insights into the sensitivity of these conflicting results.

This paper aims to fill this gap in the literature by assessing the potential effects of Germany´s energy transition on the level and volatility of electricity spot prices in Germany and in other European countries. It links the analyses of long and the short run associations, which have been traditionally investigated separately. It is noteworthy that if the ability of individual markets to overcome shocks independently is poor, then this should lead to stronger volatility transmission once markets are well connected. On the other hand, if supply or demand shocks die out quickly less volatility is expected to be transmitted. Germany serves as an example to explore long and short run associations, because of its increasing reliance on and investment in wind-generated electricity as well as the size and importance of its electricity market in Europe.

Electricity spot prices may show short term trends that reflect the energy inputs (e.g. gas), but are expected to revert to their long run mean. With increasing electricity market integration, prices should converge. Yet, unilateral national energy policies like Germany's nuclear plant closures, which significantly reduced the country's reserve margins, can impact on the speed with which electricity prices revert to their mean negatively, or increase volatility transmission. In the next section, we discuss price settings and trading arrangements and how increasing wind generation may impact on them.

3. Price setting and trading arrangements

In 1988, the principles of a European `internal market´ for goods and services were established in the Single Electricity Act. After nearly a decade of debate, EU Directive 96/92/EC defined common rules for the generation, transmission and distribution of electricity, with the aim of creating a supranational market to increase efficiency and competition in the electricity sector (Gebhardt and Höffler, 2007). Since then, several directives have followed (e.g. 2003/54/EC, 2009/72/EC), not only addressing the original aims of liberalization but also specifying paths towards the integration of renewable energy into electricity markets.

As illustrated in Figure 1, prior to the *liberalization* of the electricity sector, Germany's electricity exports rarely exceeded 5TWh per annum; interconnection with other countries was mainly in order to ensure the stable operation of the regional electricity network rather than for reasons of trade (Creti et al., 2010). Post liberalization, electricity flows have been more and more dictated by market mechanisms and, particularly in Germany, have increased significantly (BDEW, 2011).

-Figure 1 here-

Before the events in Fukushima, Germany was a net exporter of electricity with a relatively stable commercial flow with its neighbours. Exports were usually to the Benelux countries, which have a high proportion of variable peak electricity supply such as coal and gas fired plants.[3] Germany imported electricity from France, where in 2010 75.3% of electricity was produced by nuclear plants, and the Czech Republic, which also has a relatively high proportion of nuclear (32.6% or 28TWh in 2010) and fossil fuel-based generation (47.1TWh which equals 54.8%) (European Commission, 2012). Electricity flows with Denmark, Sweden and Poland are highly wind-dependent (BDEW, 2011). However, the incidents in Fukushima radically changed German import-export patterns: the average electricity export reduced to 40MWh per day between 17.03- 10.05.2011, compared to 90MWh per day between 01.02- 16.03.2011. German net importation of French electricity increased by 58%, whereas export to the Netherlands decreased by 74% for the same period (BDEW, 2011).

Following the reduction in nuclear generation capacity in Germany, the wind penetration level, defined as the ratio of wind-generated electricity to overall electricity generation, has increased. A sudden surge in wind-generated electricity can cause electricity prices locally and in connected markets to drop, because rational market players will recognize profitable arbitrage opportunities. By buying capacity in a low priced market and selling in a high cost market, price shocks can be transmitted to neighbouring markets. Equally, a sudden decrease in wind-generated electricity is more likely to result in higher electricity imports, as the reserve margin decreases.

More recently, the daily cross-border transmission capacity between countries is a result of implicit and explicit energy transactions at power exchanges (market coupling). The aim is to maximize the total economic surplus of all participants: cheaper electricity generation in one country can meet demand and reduce prices in another country, supply fluctuations can be balanced (Belpex, 2012). Since November 2010, Central Western European Market Coupling (CWE) has extended *Trilateral Market Coupling*, which connects the electricity spot markets of France, Belgium and the Netherlands to Luxembourg and Germany (Belpex, 2012). The connection of NorNed to CWE Market Coupling started in January 2011, thus linking the liquid Norwegian day-ahead market to the wider Central West European power market (APX-ENDEX, 2012).

The general aim of market coupling initiatives and interconnector is to achieve cost-reflective competitive prices and secure supply. To this end, the speed of mean reversion may prove very informative for regulators as an indicator of how quickly the supply side can react to unexpected events.

The potential effect of Germany’s energy transition on the speed of mean reversion can be assessed, as described in the next section. Since reserve margins have decreased, we therefore hypothesise:

H1: *Germany´s Energy Transition has resulted in slower mean reversion, when compared to be before the nuclear plant closures.*

If hypothesis H1 cannot be rejected, it would also be reasonable to expect stronger volatility transmission across markets, because balancing mechanisms’ needs become more reliant on inter-markets trading. Consequently, we put forward:

H2: *Germany´s Energy Transition has resulted in stronger volatility transmission of prices across markets.*

[3] In 2010 22.6TWh (19.1%) of electricity in the Netherlands was produced from solid fuels and 77.4TWh (65.5%) from gas. In Belgium 4.4% equalling 4.2TWh of total electricity is being produced by solid fuels and 33.2TWh (34.9%) by gas (European Commission, 2012).

Finally, as wind-generated electricity has priority dispatch, there should be stronger associations between the volatility of wind penetration induced by the German market and the volatility of spot prices.

H3: *Germany´s Energy Transition has resulted in stronger associations between wind penetration and spot price volatilities.*

4. Methods

This section is divided into two subsequentions: (1) methods to investigate the long run associations, in particular mean reversion and integration of time series, which are used to test H1; (2) the methods that assess short run associations, i.e. mean and volatility transmission, which are used to test the H2 and H3.

4.1. On assessing changes in mean reversion

The Fractional Integration

A process X_t is said to be *I(d)* if its fractional difference, $(1-L)^d X_t$, is a stationary *I(0)* process. The fractional difference operator $(1-L)^d$ is defined by means of a gamma function

$$(1-L)^d = \sum_{k=0}^{\infty} \frac{\Gamma(k-d)L^k}{\Gamma(-d)\Gamma(k+1)}, \tag{1}$$

where *d* can take any real value. For $-\frac{1}{2}<d<\frac{1}{2}$ the process is stationary and invertible, for $d>\frac{1}{2}$ is non-stationary, but mean reverting for $\frac{1}{2} \leq d<1$ (Robinson, 1994).

4.2. We use the semiparametric two -step Feasible Exact Local Whittle (FELW) estimator which was proposed by Shimotsu (2006). This estimator is robust to misspecification of the short run dynamics of a process (Okimoto and Shimotsu, 2010) and handles both stationary ($d<$ ½) and non-stationary ($d\geq$ ½) processes. Moreover, based on previous discussions (e.g. Robinson and Henry (1999), Shao and Wu (2007) it can be inferred that it is unlikely to be affected by conditional heteroscedasticity. As such, it is attractive when modelling electricity price series. **On assessing mean and volatility transmission**

The Multivariate Framework

Bollerslev (1990) proposed a Constant Conditional Correlation MGARCH model (CCC) to assess volatility transmission. The model is based on the decomposition of the conditional covariance matrix into conditional standard deviations and correlations. The conditional correlation matrix is time-invariant and the conditional covariance matrix can be written for each time *t*, as follows:

$$H_t = D_t \Gamma D_t = \rho_{ij}(h_{iit}\, h_{jjt})^{\frac{1}{2}} \tag{2},$$

where $1 \leq i \leq j \leq K, t = 1, \dots, N$; *K* is the number of variables in the model and *N* is the number of observations in the estimation period;

$$D_t = diag(h_{11t}^{\frac{1}{2}} \dots h_{KKt}^{\frac{1}{2}}), \tag{3}$$

$$\Gamma = \rho_{ij} \tag{4}$$

h_{iit} is the conditional variance of the univariate GARCH model and Γ is the symmetric positive definite constant conditional correlation matrix, with $\rho_{ii} = 1, \forall i$.

Tse and Tsui (2002) and Engle (2002) extended the CCC models to *dynamic* conditional correlation models (DCC), as the assumption of constant correlations may be too restrictive (Minović, 2009). The authors include a time dependent conditional correlation matrix (Γ_t), thus the conditional covariance matrix becomes:

$$H_t = D_t \Gamma_t D_t \tag{5}$$

Where D_t and h_{iit} are as defined in equation (2).

Following, Tse and Tsui (2002) the conditional correlation matrix is given by:

$$\Gamma_t = (1 - \theta_1 - \theta_2)\Gamma + \theta_2 \Gamma_{t-1} + \theta_1 \Psi_{t-1}, \tag{6}$$

where $1 \leq i \leq j \leq K$ and θ_1 and θ_2 are non-negative constants such that$\theta_1 + \theta_2 < 1$ and Γ, is the KxK symmetric positive definite constant parameter matrix with $\rho_{ii} = 1$ for all *i*. Ψ_{t-1} is a function of the lagged standardized residuals ξ_{it}, and its *ijth* element can be denoted as:

$$\Psi_{t-1,ji} = \frac{\sum_{m=1}^{M} \xi_{i,t-m}\, \xi_{j,t-m}}{\sqrt{(\sum_{m=1}^{M} \xi_{i,t-m}^2)(\sum_{m=1}^{M} \xi_{j,t-m}^2)}}$$

where

$$\xi_{it} = e_{it}/h_{iit}^{\frac{1}{2}} \tag{7}$$

Engle (2002) proposed the following alternative formulation:

$$\Gamma_t = diag\left(q_{11t}^{-\frac{1}{2}} \dots q_{KKt}^{-\frac{1}{2}}\right)\left((1 - \theta_1 - \theta_2)\bar{Q} + \theta_1 \xi_{t-1}\xi_{t-1}' + \theta_2 Q_{t-1}\right) diag\left(q_{11t}^{-\frac{1}{2}} \dots q_{KKt}^{-\frac{1}{2}}\right), \tag{8}$$

where $\bar{Q}$ is the KxK unconditional correlation matrix of ξ_t, and θ_1 and θ_2 are non-negative parameters satisfying $\theta_1 + \theta_2 < 1$ (Higgs, 2009).

5. Data

The dataset consists of hourly electricity spot prices from eight European wholesale markets: APX-NL (Netherlands), Belpex (Belgium), EPEX-DE (Germany, Switzerland), Nord Pool (Denmark, Finland, Sweden), APX-UK (UK), OMEL (Spain, Portugal) and EPEX-FR (France), covering the period from 02.11.2009 to 09.10.2012. Since hourly spot prices have multiple seasonalities we focus on the week-daily mean average prices, thus reducing the sample to 767 observations for each market. This is a common approach in the literature (Chan and Gray, 2006; De Vany and Walls, 1999; Escribano et al., 2002; Higgs and Worthington, 2005; Koopman et al., 2007; Lucia and Schwartz, 2002; Robinson, 2000; Wolak, 2000; Worthington et al., 2005) and is suitable for this study, since the influence of wind forecast on spot prices has been shown to be more relevant on a daily rather than hourly basis (Neubarth et al., 2006).

The hourly forecasts and actual electricity output generated by wind has been obtained from the Transparency in Energy Markets EEX database (http://www.transparency.eex.com/en/). We converted the data into a week-daily frequency and divided it by the volumes traded on the spot market to create the \`penetration´ and \`pl. penetration´ variables. Figure 2 depicts German electricity spot prices and the actual wind penetration on a common scale and illustrates the negative association between the two variables.

-Figure 2 here-

Table 1 summarises the time series: \`planned wind´ and \`actual wind´, which is electricity generated by wind in MWh, the electricity spot prices in EUR/MWh and wind penetration variables \`penetration´ and \`pl. penetration´.[4] The statistics reject normality, as the Jarque-Bera statistics exceed their critical values; all markets, excluding OMEL, exhibit positive skewness and high kurtosis, with the exception of Nord Pool. These fat-tailed distributions reflect the many spikes in the data. The hypothesis of a unit root (ADF Test) is rejected for all series, thus confirming that the time series do not have a significant trend component. This is in line with the long memory parameter *d* estimated with the Geweke/Porter-Hudak (1983) (GPH), Robinson and Henry (1998) (Robinson), Exact Local Whittle (ELW) and two step Feasible Exact Local Whittle (FELW).

-Table 1 here-

6. Estimation Results

6.1. Mean reversion and integration

By the 6th of August 2011 the total of eight nuclear power plants, corresponding to a gross capacity of 8811MWh, had been removed from the German electricity network owing to its energy transition (BMBW, 2011). Figure 3 indicates that after Germany' s energy transition (6^{th} of August is value 1232) electricity spot prices are divergent. A Chow (1960) breakpoint test, which is the most commonly used test for the presence of a structural break with known date will therefore be utilized in the next section.

-Figure 3 here-

The sample means of estimated *ds* for the 260 observations before and after 6.08.2011, which cover one year before and after Germany´s energy transition, are tested for significant changes in mean. The sample means, their confidence intervals and results of t-tests are summarised in Table 2. According to these results, the long memory parameter *d* has increased for all markets that are directly linked to Germany at a 5% significant level, with the exception of OMEL.

[4] In earlier preliminary study we included natural gas (Zeebrugge) and crude oil prices (Brent) in the analysis, as well as hourly forecasts and actual electricity output generated by solar. However, associations were barely significant and therefore we focus on daily data and excluded the other variables in the present study. In the particular case of solar, the lack of significant associations could be due to either the limited amount of available data or the relatively small solar electricity output.

-Table 2 here-

6.2. Mean and volatility transmission

Univariate models are estimated to assess mean spillovers between markets and planned wind penetration levels. Their coefficients, respective standard errors and *t*-values, for each spot market, are displayed in Table 3. The significant results (printed in bold) suggest that all markets exhibit significant positive own mean spill over. In Germany, an increase of 1EUR/MWh can lead to an increase of 0.14EUR/MWh the following day. By contrast, in the case of the Nord Pool, the same increase could result in an increase of 0.97 EUR/MWh the next day, thus indicating high persistence in the spot price processes. German spot prices also have a significant and positive relationship with the lagging Dutch, UK, Nord Pool, Swiss and OMEL prices, as indicated in column 2 of Table 3. The planned German wind penetration level is negatively associated with Swiss, German, Nord Pool, Dutch and Belgian electricity spot prices.

-Table 3 here-

In order to analyse the potential effect of reduced base-load capacity in Germany, we investigate the transmission of volatility to other markets that might have been caused by German wind farms. For the evaluation of constant and time-varying correlations of the volatilities, we divide the dataset into two sub samples Again, we chose the 6th of August 2011 as the date to split the sample, since by then a total of eight nuclear power plants, a gross capacity of 8811MWh, had been removed from the electricity network (BFS, 2012). The results of the CCC model prior to the nuclear phase out suggest that between 32 and 33 of the 36 correlations are significant for planned as well as actual penetration levels; all constant correlations between electricity spot price volatilities are positive. For actual wind penetration, correlations with spot price volatilities range between .10 (OMEL and Germany) and .98 (Belgium and France) and for planned wind penetration between .09 (OMEL and Germany) and .98 (Belgium and France). Post August 2011, 32 of the estimated correlations remain significant, most of which have increased significantly. Compared to the other markets, OMEL and Nord Pool are characterized by comparatively fewer significant correlations, which are also comparably lower, with highest values of .24 for OMEL and .4 for Nord Pool before the nuclear phase-out. In the case of OMEL, this finding can be explained by the limited physical interconnection, particularly with France, which amounted to only 3% of Spain's electricity generation, compared to the recommended 10% (Bilbao et al., 2011).[1] Nord Pool is better connected to other European countries. However, the Nordic markets are more resilient against volatility shocks due to the large proportion of hydro-based electricity in Norway (Deidersen and Trück, 2002).

The associations of the wind penetration variables and European electricity spot prices are negative. We find that the number of significant correlations between wind penetration and spot price volatilities remains the same; however, they increased in strength when compared to the period prior to August 2011. Despite the fact that electricity prices are set before actual power delivery, implying that forecasts, rather than actual metered output should be more likely to affect the market clearing process (Gil et al., 2012), we do not find stronger associations for actual (compared to planned) wind penetration with spot prices. The CCC model suggests that the negative correlation between wind penetration variability and electricity spot price volatility in France has more than doubled for actual and planned penetration level from the previous -.16 to -.41 and -.16 to -.39 respectively. In Germany, the correlation has also increased significantly for actual penetration from -.48 to -.59 and from -.52 to -.56 for planned penetration levels. Likewise for Belgium, we observe a significant increase from -.18 to -.40 for actual penetration and -.17 to -.37 for planned wind penetration. The Spanish and Portuguese OMEL market is an exception, since there is no significant correlation between its prices and wind penetration volatilities.

Based on a likelihood ratio test, we compare the fit of the model of constant conditional correlations with the time-varying alternative model (by testing the null hypothesis $\theta_1 = \theta_2 = 0$). With a critical 5% value for 36 degrees of freedom, the Chi-square statistic is 50.998. Therefore the hypothesis of constant conditional correlations is rejected in favour of the time-varying alternative for all four datasets.

According to the Akaike Information Criterion (AIC) and the Schwarz Information Criterion (SIC), neither Engle´s (2002) Dynamic Conditional Correlation (EDCC) nor Tse and Tsui (2002) (TTDCC) specifications can be preferred. Both models suggest positive correlations between electricity spot price volatilities and negative correlations between wind penetration and electricity spot prices. The correlation coefficients are similar to the estimates of the CCC model. There are fewer significant correlation coefficients for actual as opposed to planned penetration level, as well as when we compare correlation estimates prior to Germany's nuclear moratorium, most noticeably in the case of the TTDCC model specification. We also notice a significant increase in the correlation coefficients after August 2011 compared to before. The dynamic conditional correlations (EDCC) for the pairs Belgium-France and Switzerland-UK are depicted in Figure 4, which shows that the association is stronger and more stable in the case of France-Belgium. In contrast, the correlation of volatilities between Switzerland and UK is much weaker and more unstable.

-Figure 4 here-

The time-varying conditional correlation coefficients $(\boldsymbol{\theta_1}, \boldsymbol{\theta_2})$ for both the TTDCC and EDCC models sum to less than one, suggesting that the correlations are mean-reverting processes and thus do not increase over time. The coefficient $\boldsymbol{\theta_1}$ shows the effect of an innovation on the correlation coefficients and is relatively small when compared to $\boldsymbol{\theta_2}$, which shows the persistence of correlation association. There are no significant changes in the estimates of the time-varying coefficients when comparing the periods prior to and post nuclear phase out in Germany.

-Table 4 here-

-Table 5 here-

-Table 6 here-

7. Summary and Conclusion

This study shows that decisions made by one European state can impact on short run associations of neighbouring or connected markets as well as on long run convergence. Univariate models suggest that high levels of forecast wind penetration in Germany may be linked to price falls in four neighbouring electricity spot markets (Nord Pool, Netherlands, Switzerland and Belgium) as well as with the German market. Assessing mean reverting behaviour of electricity spot prices the study has shown that since the German energy transition shocks are less easily overcome in Germany and neighbouring markets. In addition, the short run volatility transmission in the spot markets has increased, while the speed of long run mean reversion has decreased.. Furthermore, the results confirm the expectation that physically well-connected and coupled electricity markets exhibit significant and positive volatility spillages.

The significant negative associations between the variances of forecast wind penetration and spot price can be explained by wind-generated electricity having priority dispatch (Bundesgesetzblatt, 1990). In Germany all RES-E generators are exempted from balancing responsibilities. Forecasting, balancing and scheduling are obligations of the local transmission system operator, which is also responsible for connecting new renewable energy. However, transmission system operators in Germany and other countries are not obliged to minimise forecasting errors, which can increase price volatility (Klessmann et al., 2008).

The slower mean reverting behaviour of electricity spot markets as well as stronger associations between wind penetration and spot price volatility observed after August 2011 may reflect a shift in the merit order curve. Although the electricity traded on the German spot market and wind penetration levels (related to traded volumes on the spot) do not suggest significant changes after the closures of nuclear power plants, reserve margins have decreased and therefore changed the trade pattern (decreased exports and increased imports) since March 2011 (BDEW, 2011). Furthermore, with the increasing share of wind-generated electricity in European markets, the transmission of volatilities between neighbouring markets will be further facilitated.

The Nuclear Phase-Out Act out will expand the 5% gap in Germany's electricity capacity in 2011 to 23% by 2022. Meanwhile, RESA 2012 aims to increase electricity generated from RES-E, likely resulting in wind penetration levels increasing. Within the local electricity market, demand response and electricity storage technologies can deal with the variability and unpredictability of RES-E. At the European level, a less unilateral tool is the supergrid, which should encourage better management of resources complementarities and encourage electricity trade. Well-managed imports and exports would help individual markets to stabilise prices and secure supply in cases of scarcity like a nuclear phase out (van Ackere and Ochoa, 2009). 2014 is set as the deadline for the completion of an internal electricity market and 2015 the year by which the *`energy islands´* of Europe should be connected (European Commission, 2002). Interconnection enables surplus electricity to be exported or imported depending on generated output, but several of Germany´s trade partners rely on fossil fuels and nuclear generators, some of which are also likely to be phased out and replaced by RES-E. Investment in flexible back-up capacity remains necessary. However, as this study shows, higher wind penetration in one country can reduce load factors of conventional generators in interconnected markets. Consequently, the ability of peak and mid-merit plants to recover their fixed costs is weakened, thus leading to earlier decommissioning and discouraging new investment thereby further deteriorating the system's ability to respond to demand peaks.

In conclusion, the results of the present study highlight the challenges associated with Germany's Energy Transition in the context of achieving the goal of a single European electricity market. The reported findings call for a consensus approach to the efficient management of complementarities of national energy mixes, thereby facilitating the transition towards a low carbon economic system.

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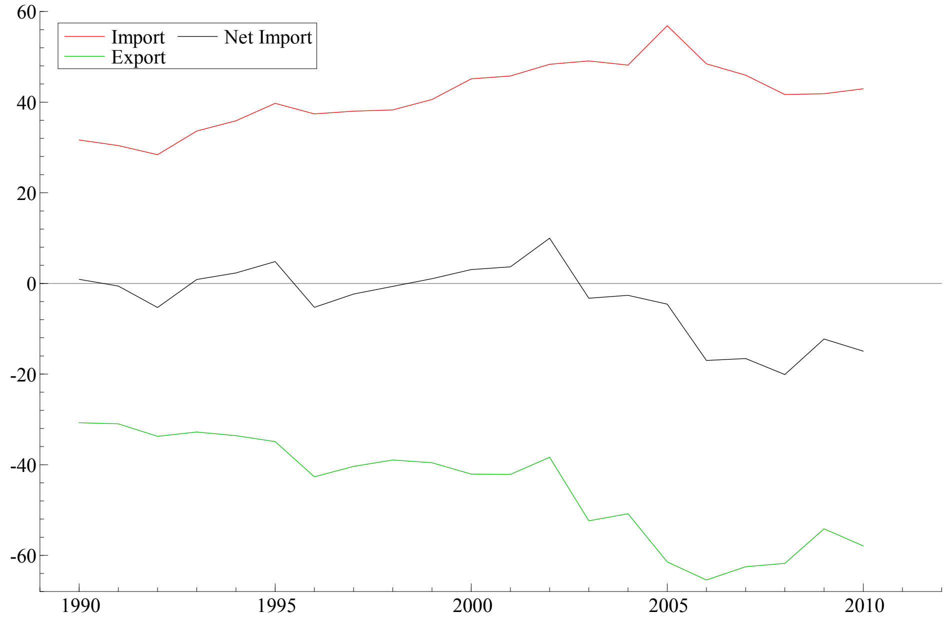

Figure 1: Import-Export of electricity in Germany in MWh since 1990. Source: European Commission 2012

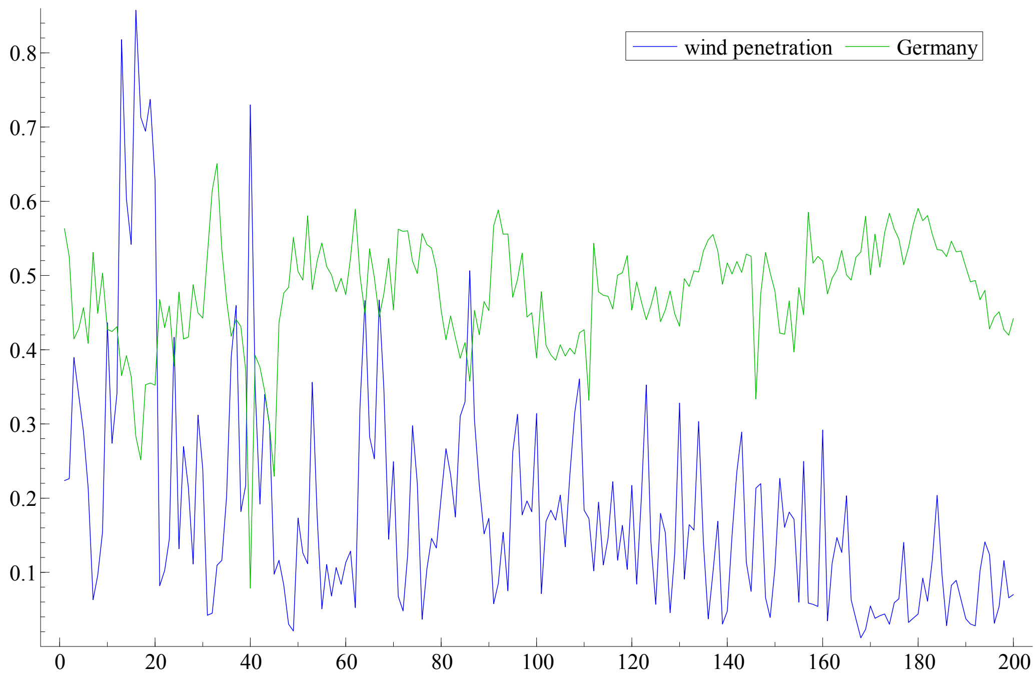

Figure 2: Wind penetration variable and German electricity spot price on a common scale from 02/11/2009 to 06/08/2010

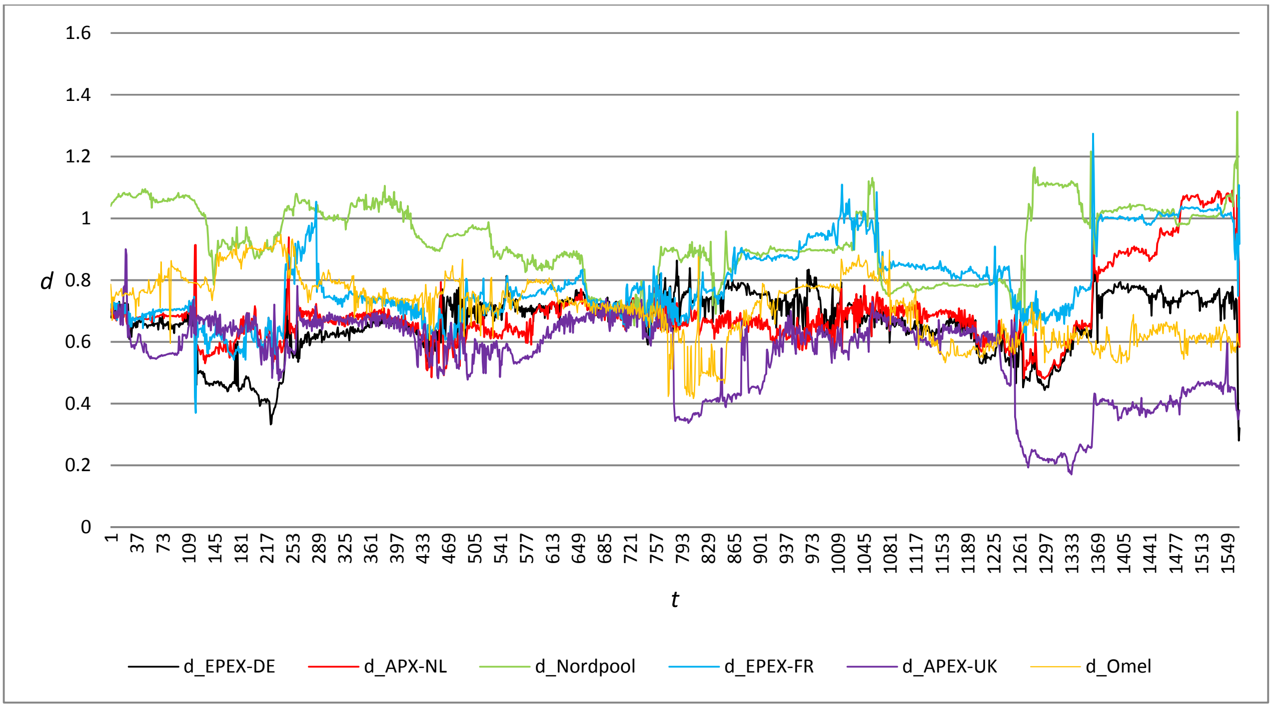

Figure 3 Time varying long memory parameter d for electricity spot prices. Window200 and bandwidth m=54 from February 2006 to November 2012.

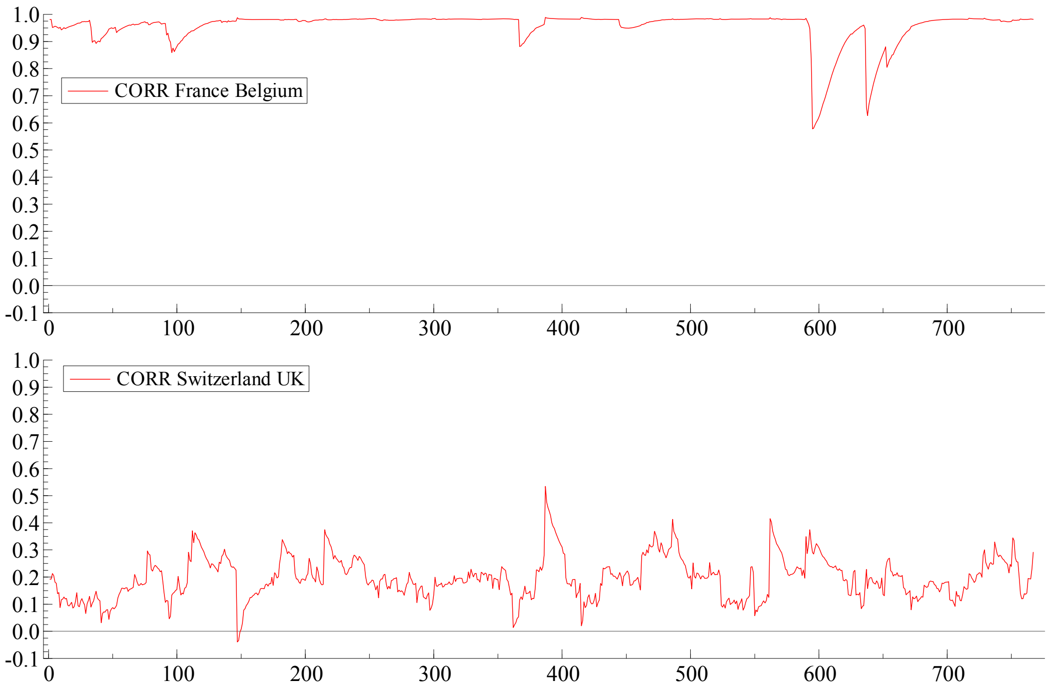

Figure 4: Dynamic Conditional Correlations (EDCC) for France and Belgium as well as for Switzerland and UK.

	EPEX-FR	Swiss	EPEX-DE	APX-NL	Nord Pool	Omel	APX-UK	Belpex	Pntr.	Pl. Pntr.
Min	15.13	15.66	7.21	21.04	7.94	3.13	30.52	15.11	0.01	0.02
Mean	51.04	55.33	48.98	50.08	45.205	44.5	52.12	49.86	0.18	0.19
Max	367.6	155.32	98.98	98.98	134.8	67.35	130.81	111.92	0.86	0.85
Std.Dev	15.65	11.63	8.61	7.7	16.61	10.18	8.81	9.53	0.13	0.13
Skew.	11.45	1.85	0.17	0.32	0.63	-1.05	1.46	0.94	1.37	1.3
Kurt.	219.22	13.27	2.84	3.24	1.55	1.49	11.27	5.76	2.42	2.11
JB	1552500	284.54	262.35	348.36	162.77	210.44	4327.6	1174.1	425.32	357.68
ADF	-13.45	-8	-10.26	-8.8	-4.19	-7.4	-10.62	-9.42	-14.07	-14.34
GPH	0.439 [.366; .5124]	0.728 [.654; .801]	0.563 [.492; .639]	0.621 [.548; .695]	0.797 [.724; .870]	0.615 [.542; .689]	0.504 [.430; .577]	0.635 [.561; .708]	-	-
Robinson	0.436 [.386; .486]	0.648 [.598; .598]	0.502 [.451; .552]	0.565 [.5143; .6145]	0.740 [.690; .790]	0.549 [.500; .599]	0.438 [.388; .488]	0.574 [.494; .624]	-	-
ELW (m=0.6)	0.239 [.106; .372]	0.443 [.310; .576]	0.421 [.288;.555]	0.431 [.298; .564]	0.722 [.589; .856]	0.700 [.566;.833]	0.638 [.505 ; .387]	.387 [.254; .520]	-	-
FELW (m=0.6)	0.242 [.108 ; .375]	0.447 [.314 ; .580]	0.431 [.297 ;.564]	0.433 [.300 ;.567]	0.705 [.572 ;.838]	0.691 [.558 ; .824]	0.637 [.503 ; .770]	0.391 [.258; .525]	-	-

Table 1: Minimum (min), mean, maximum (max), standard deviation (std. dev) shown in EUR/MWh; skewness (skew.), excess kurtosis (kurt.), Jarque Bera statistic (JB), Augmented Dickey Fuller Test with constant (ADF) critical value for 1%=-3.44 and 5%= -2.87. Long memory estimators Geweke/Porter-Hudak (1983) (GPH), Robinson and Henry (1998) (Robinson), Exact Local Whittle (ELW) and two step Feasible Exact Local Whittle (FELW) with bandwidth m=0.6. Confidence Intervals in parentheses. Planned (Pl. Pntr.) and Actual Wind Penetration (Pntr.) in MWh, EPEX-FR, EPEX-DE, APX-NL, Nord Pool, OMEL, APX-UK, Belpex in EUR/MWh, sample size 767.The series are untreated.

			$\bar{d}$ and CI	t-statistic
Germany´s nuclear phase out 6.08.2011	EPEX-DE	d_before	0.5914 [.458; .7281]	2.130*
		d_after	0.7363 [.6029; .8697]	
	EPEX-FR	d_before	0.7926 [.6592;.926]	2.994**
		d_after	0.9963 [.8629; 1.130]	
	APX-NL	d_before	0.6243 [.4909; .7577]	4.225**
		d_after	0.9118 [.7784; 1.045]	
	Belpex	d_before	0.7916 [.6582;.925]	2.847**
		d_after	0.9853 [.8519; 1.119]	
	Nordpool	d_before	0.7844 [.65104; .9177]	1.708*
		d_after	1.0122 [.8788; 1.1455]	
	OTE	d_before	0.4072 [.2738; .5406]	6.736**
		d_after	0.8655 [.7321; .9989]	
	OMEL	d_before	0.5707	0.862
		d_after	0.6294	

Table 2: Germany's nuclear phase out long memory estimates d for n=260, w=200, m=54 and iterations=100. The asterix * and ** denote 5% and 1% significance level respectively. Critical values for the one sided test are 5%= 1.645 and 1%=2.326 and for the two sided test 5%= 1.960 and 1%= 2.576. The series have been outlier treated.**5**

[5] Outliers were defined by surpassing a threshold of the rolling window mean average +/- 3 standard deviations over 1 month period. After five iterations convergence has been achieved.

	France		*Germany*		*NL*		*Nord Pool*		*OMEL*		*Switzerland*		*UK*		*Belgium*	
	Coef. Std. error	*t-value*	*Coef. Std. error*	*t-value*	*Coef. Std. error*	*t-value*	*Coef. Std. error*	*t-value*	*Coef. Std. error*	*t-value*	*Coef. Std. error*	*t-value*	*Coef. Std. error*	*t-value*	*Coef. Std. error*	*t-value*
FR_1	***0.16***	*3.50*	*0.03*	*1.42*	*0.01*	*0.72*	*0.00*	*0.19*	*0.01*	*0.28*	*-0.02*	*-0.64*	*0.01*	*0.61*	***-0.06***	*-2.60*
	0.05		*0.02*		*0.02*		*0.02*		*0.02*		*0.03*		*0.02*		*0.02*	
Constant	*-5.88*	*-1.82*	***9.62***	*7.21*	***10.07***	*8.68*	***4.56***	*3.20*	***3.36***	*2.37*	***5.84***	*3.28*	***8.16***	*5.04*	***5.75***	*3.59*
	3.23		*1.33*		*1.16*		*1.43*		*1.42*		*1.78*		*1.62*		*1.60*	
GER_1	***-0.33***	*-2.45*	***0.14***	*2.48*	*-0.04*	*-0.77*	***-0.15***	*-2.47*	*-0.05*	*-0.85*	***-0.26***	*-3.47*	*-0.08*	*-1.22*	***-0.25***	*-3.74*
	0.13		*0.06*		*0.05*		*0.06*		*0.06*		*0.07*		*0.07*		*0.07*	
NL_1	***0.54***	*3.13*	***0.35***	*4.88*	***0.51***	*8.31*	*0.00*	*0.05*	***0.30***	*4.01*	***0.25***	*2.66*	***0.29***	*3.32*	***0.17***	*2.02*
	0.17		*0.07*		*0.06*		*0.08*		*0.08*		*0.09*		*0.09*		*0.09*	
NP_1	*0.04*	*1.32*	***0.09***	*6.56*	***0.06***	*5.33*	***0.97***	*67.80*	***-0.07***	*-4.97*	***0.06***	*3.54*	***0.05***	*3.17*	***0.07***	*4.30*
	0.03		*0.01*		*0.01*		*0.01*		*0.01*		*0.02*		*0.02*		*0.02*	
OMEL_1	*-0.10*	*-1.71*	***0.14***	*6.08*	***0.12***	*6.10*	*0.02*	*0.73*	***0.74***	*30.00*	*0.01*	*0.26*	***0.16***	*5.83*	***0.08***	*2.80*
	0.06		*0.02*		*0.02*		*0.02*		*0.02*		*0.03*		*0.03*		*0.03*	
CH_1	***0.22***	*3.35*	***0.17***	*6.20*	***0.10***	*4.31*	*0.04*	*1.51*	***-0.06***	*-1.91*	***0.79***	*21.70*	***-0.07***	*-2.05*	***0.20***	*6.15*
	0.07		*0.03*		*0.02*		*0.03*		*0.03*		*0.04*		*0.03*		*0.03*	
UK_1	*0.02*	*0.26*	***0.06***	*2.21*	***0.09***	*4.26*	*0.02*	*0.70*	*0.08*	*2.83*	*0.00*	*0.06*	***0.56***	*18.10*	***0.07***	*2.29*
	0.06		*0.03*		*0.02*		*0.03*		*0.03*		*0.03*		*0.03*		*0.03*	
BEL_1	***0.56***	*5.14*	***-0.10***	*-2.11*	*-0.02*	*-0.38*	*0.01*	*0.22*	*-0.06*	*-1.24*	*0.08*	*1.32*	*-0.04*	*-0.68*	***0.62***	*11.50*
	0.11		*0.05*		*0.04*		*0.05*		*0.05*		*0.06*		*0.05*		*0.05*	
Pl. pntr	*-4.31*	*-1.26*	***-20.73***	*-14.70*	***-13.58***	*-11.00*	***-6.17***	*-4.08*	*2.21*	*1.47*	***-4.26***	*-2.26*	*-1.81*	*-1.05*	***-9.55***	*-5.63*
	3.42		*1.41*		*1.23*		*1.51*		*1.50*		*1.89*		*1.72*		*1.70*	

Table 3: Univariate Model estimate. FR_1 lagged French spot price; GER_1: 1 lagged German spot price; NL_1 1 lagged Netherlands spot price; NP_1 1 lagged Nord Pool spot price; CH_1: 1 lagged Switzerland; ES_1 1 lagged OMEL spot price; UK_1: 1 lagged UK spot price; BEL_1 1 lagged Belgium spot price; Pl. pntr. Planned wind penetration level. Standard errors in parentheses; significant values are printed in bold.

	Actual						*Planned*					
	Coef.	*Std. error*	*t-value*	*Coef.*	*Std. error*	*t-value*	*Coef.s*	*Std. error*	*t-value*	*Coef.*	*Std. error*	*t-value*
ρ_{21}	**0.63**	0.03	22.92	**0.80**	0.02	35.08	**0.63**	0.03	24.62	**0.80**	0.02	34.44
ρ_{31}	**0.75**	0.02	32.54	**0.83**	0.02	44.81	**0.75**	0.02	34.13	**0.83**	0.02	44.36
ρ_{41}	**0.24**	0.06	3.85	**0.28**	0.05	5.16	**0.24**	0.06	3.88	**0.28**	0.05	5.26
ρ_{51}	**0.21**	0.04	4.75	**0.25**	0.06	4.13	**0.21**	0.04	4.81	**0.24**	0.06	4.06
ρ_{61}	**0.56**	0.04	14.31	**0.67**	0.03	20.17	**0.56**	0.04	14.50	**0.66**	0.03	19.58
ρ_{71}	**0.21**	0.04	5.24	**0.24**	0.05	4.41	**0.21**	0.04	5.13	**0.24**	0.05	4.40
ρ_{81}	**0.98**	0.00	249.90	**0.96**	0.01	131.60	**0.98**	0.00	249.80	**0.96**	0.01	131.00
ρ_{91}	**-0.16**	0.04	-3.93	**-0.41**	0.05	-8.88	**-0.16**	0.04	-3.52	**-0.39**	0.05	-8.63
ρ_{32}	**0.81**	0.02	40.90	**0.84**	0.02	46.06	**0.81**	0.02	42.05	**0.84**	0.02	45.67
ρ_{42}	**0.40**	0.05	8.57	**0.34**	0.05	6.26	**0.40**	0.05	8.61	**0.34**	0.05	6.40
ρ_{52}	**0.10**	0.04	2.16	**0.19**	0.06	3.10	**0.09**	0.04	2.13	**0.19**	0.06	3.01
ρ_{62}	**0.49**	0.03	14.88	**0.70**	0.03	21.74	**0.49**	0.03	14.81	**0.70**	0.03	21.16
ρ_{72}	**0.23**	0.04	6.08	**0.22**	0.05	4.20	**0.23**	0.04	6.16	**0.22**	0.05	4.19
ρ_{82}	**0.64**	0.03	23.62	**0.83**	0.02	41.60	**0.65**	0.03	25.42	**0.83**	0.02	40.86
ρ_{92}	**-0.48**	0.03	-15.28	**-0.59**	0.03	-16.83	**-0.52**	0.03	-17.14	**-0.56**	0.04	-15.52
ρ_{43}	**0.32**	0.05	6.06	**0.26**	0.06	4.64	**0.32**	0.05	6.23	**0.26**	0.06	4.79
ρ_{53}	**0.15**	0.04	3.45	**0.14**	0.06	2.31	**0.15**	0.04	3.44	**0.13**	0.06	2.19
ρ_{63}	**0.59**	0.03	17.20	**0.67**	0.03	21.59	**0.59**	0.03	17.00	**0.67**	0.03	20.79
ρ_{73}	**0.25**	0.04	6.77	**0.24**	0.05	4.69	**0.25**	0.04	6.79	**0.24**	0.05	4.71
ρ_{83}	**0.77**	0.02	36.15	**0.88**	0.02	55.09	**0.78**	0.02	38.11	**0.88**	0.02	54.92
ρ_{93}	**-0.43**	0.03	-12.70	**-0.48**	0.04	-11.43	**-0.44**	0.03	-13.11	**-0.45**	0.04	-10.50
ρ_{54}	-0.02	0.05	-0.36	0.09	0.05	1.71	-0.01	0.05	-0.27	0.09	0.05	1.81
ρ_{64}	**0.18**	0.05	3.60	**0.26**	0.06	4.55	**0.18**	0.05	3.71	**0.27**	0.06	4.70
ρ_{74}	**0.21**	0.04	4.73	0.08	0.05	1.69	**0.20**	0.04	4.66	0.08	0.05	1.68
ρ_{84}	**0.26**	0.06	4.25	**0.25**	0.06	4.48	**0.26**	0.06	4.30	**0.26**	0.06	4.61
ρ_{94}	**-0.20**	0.04	-4.98	**-0.29**	0.05	-5.82	**-0.21**	0.04	-5.04	**-0.30**	0.05	-5.99
ρ_{65}	**0.22**	0.04	5.20	**0.15**	0.06	2.39	**0.22**	0.04	5.28	**0.15**	0.07	2.36
ρ_{75}	-0.02	0.04	-0.46	-0.04	0.05	-0.81	-0.02	0.04	-0.47	-0.04	0.05	-0.77
ρ_{85}	**0.21**	0.04	4.86	**0.21**	0.06	3.43	**0.21**	0.04	4.89	**0.21**	0.06	3.37
ρ_{95}	0.01	0.04	0.32	-0.07	0.05	-1.27	0.01	0.04	0.20	-0.08	0.06	-1.43
ρ_{76}	**0.16**	0.04	4.07	**0.17**	0.05	3.24	**0.16**	0.04	4.17	**0.17**	0.05	3.17
ρ_{86}	**0.55**	0.04	14.06	**0.70**	0.03	22.73	**0.55**	0.04	14.25	**0.69**	0.03	21.89
ρ_{96}	**-0.24**	0.04	-5.60	**-0.29**	0.05	-6.11	**-0.26**	0.04	-6.06	**-0.27**	0.05	-5.51
ρ_{87}	**0.23**	0.04	5.66	**0.25**	0.05	4.72	**0.22**	0.04	5.57	**0.25**	0.05	4.72
ρ_{97}	**-0.13**	0.04	-3.24	**-0.17**	0.05	-3.42	**-0.13**	0.04	-3.06	**-0.16**	0.05	-3.20
ρ_{98}	**-0.18**	0.04	-4.29	**-0.40**	0.05	-8.65	**-0.17**	0.04	-3.80	**-0.37**	0.05	-8.18
AIC	38.65693			39.87573			38.47086			39.84202		
SIC	39.31254			40.76191			39.12647			40.72821		
LnL	-8818.09			-6047.92			-8775.298			-6042.750		
LR test	384.736			78.018			384.314			78.716		

Table 4: Constant conditional correlations estimation results - ρij is the correlation between variable i and j. (1 for France; 2- Germany; 3- Netherlands; 4- Nord Pool; 5- Spain; 6-Switzerland; 7-UK; 8- Belgium; 9: wind penetration .standard errors and p-values for the conditional correlations: AIC and SIC are the Akaike Information Criterion and Schwartz Criteria, respectively. LnL is the log likelihood, LR test: θ 1 =θ 2 =0 (constant correlation assumption); significant values are printed in bold.

	Prior to phase out			*Post phase out*			*Prior to phase out*			*Post phase out*		
	Coef.	*Std. error*	*t-value*	*Coef..*	*Std. error*	*t-value*	*Coef..*	*Std. error*	*t-value*	*Coef.*	*Std. error*	*t-value*
ρ_{21}	***0.71***	*0.04*	*19.64*	***0.84***	*0.03*	*32.82*	***0.72***	*0.03*	*20.98*	***0.84***	*0.03*	*32.31*
ρ_{31}	***0.83***	*0.03*	*30.23*	***0.86***	*0.02*	*41.89*	***0.84***	*0.03*	*32.74*	***0.86***	*0.02*	*41.05*
ρ_{41}	***0.26***	*0.08*	*3.23*	***0.29***	*0.06*	*4.67*	***0.26***	*0.08*	*3.24*	***0.30***	*0.06*	*4.75*
ρ_{51}	***0.21***	*0.06*	*3.33*	***0.24***	*0.07*	*3.51*	***0.20***	*0.06*	*3.20*	***0.24***	*0.07*	*3.44*
ρ_{61}	***0.58***	*0.05*	*11.60*	***0.69***	*0.04*	*18.16*	***0.58***	*0.05*	*11.83*	***0.68***	*0.04*	*17.73*
ρ_{71}	***0.19***	*0.06*	*3.27*	***0.25***	*0.06*	*4.05*	***0.19***	*0.06*	*3.35*	***0.25***	*0.06*	*3.97*
ρ_{81}	***1.00***	*0.00*	*782.70*	***0.97***	*0.01*	*183.90*	***1.00***	*0.00*	*799.10*	***0.97***	*0.01*	*185.50*
ρ_{91}	***-0.18***	*0.06*	*-2.83*	***-0.43***	*0.06*	*-7.74*	***-0.18***	*0.06*	*-2.82*	***-0.42***	*0.05*	*-7.76*
ρ_{32}	***0.83***	*0.03*	*29.93*	***0.88***	*0.02*	*37.51*	***0.83***	*0.03*	*30.70*	***0.88***	*0.02*	*37.46*
ρ_{42}	***0.39***	*0.07*	*5.72*	***0.34***	*0.06*	*5.50*	***0.39***	*0.07*	*5.89*	***0.34***	*0.06*	*5.63*
ρ_{52}	*0.11*	*0.06*	*1.77*	***0.20***	*0.07*	*2.94*	***0.10***	*0.06*	*1.64*	***0.20***	*0.07*	*2.86*
ρ_{62}	***0.54***	*0.05*	*11.65*	***0.72***	*0.04*	*19.16*	***0.54***	*0.05*	*11.59*	***0.72***	*0.04*	*19.12*
ρ_{72}	***0.19***	*0.06*	*3.39*	***0.23***	*0.06*	*3.59*	***0.20***	*0.06*	*3.54*	***0.22***	*0.06*	*3.52*
ρ_{82}	***0.71***	*0.04*	*19.96*	***0.84***	*0.02*	*34.23*	***0.72***	*0.03*	*21.30*	***0.84***	*0.02*	*33.76*
ρ_{92}	***-0.42***	*0.05*	*-8.66*	***-0.58***	*0.04*	*-13.43*	***-0.46***	*0.05*	*-10.08*	***-0.55***	*0.04*	*-12.62*
ρ_{43}	***0.32***	*0.07*	*4.38*	***0.27***	*0.06*	*4.23*	***0.32***	*0.07*	*4.52*	***0.28***	*0.06*	*4.37*
ρ_{53}	***0.15***	*0.06*	*2.54*	***0.15***	*0.07*	*2.28*	***0.15***	*0.06*	*2.42*	***0.15***	*0.07*	*2.19*
ρ_{63}	***0.65***	*0.04*	*14.61*	***0.70***	*0.03*	*20.00*	***0.65***	*0.04*	*14.46*	***0.70***	*0.04*	*19.66*
ρ_{73}	***0.23***	*0.05*	*4.11*	***0.24***	*0.06*	*3.98*	***0.23***	*0.05*	*4.25*	***0.24***	*0.06*	*3.94*
ρ_{83}	***0.84***	*0.03*	*31.71*	***0.90***	*0.02*	*47.31*	***0.84***	*0.02*	*34.41*	***0.90***	*0.02*	*46.68*
ρ_{93}	***-0.40***	*0.05*	*-7.67*	***-0.49***	*0.05*	*-9.68*	***-0.42***	*0.05*	*-8.13*	***-0.46***	*0.05*	*-9.13*
ρ_{54}	*0.01*	*0.06*	*0.09*	*0.09*	*0.06*	*1.40*	*0.01*	*0.06*	*0.12*	*0.09*	*0.06*	*1.45*
ρ_{64}	***0.22***	*0.06*	*3.48*	***0.27***	*0.07*	*4.03*	***0.22***	*0.06*	*3.55*	***0.28***	*0.07*	*4.16*
ρ_{74}	***0.21***	*0.06*	*3.46*	*0.08*	*0.06*	*1.36*	***0.20***	*0.06*	*3.39*	*0.08*	*0.06*	*1.35*
ρ_{84}	***0.27***	*0.08*	*3.29*	***0.26***	*0.07*	*3.99*	***0.26***	*0.08*	*3.30*	***0.27***	*0.07*	*4.11*
ρ_{94}	***-0.19***	*0.05*	*-3.41*	***-0.28***	*0.06*	*-4.83*	***-0.20***	*0.06*	*-3.48*	***-0.29***	*0.06*	*-4.91*
ρ_{65}	***0.20***	*0.06*	*3.29*	***0.16***	*0.07*	*2.20*	***0.20***	*0.06*	*3.29*	***0.16***	*0.07*	*2.22*
ρ_{75}	*-0.01*	*0.06*	*-0.21*	*-0.02*	*0.06*	*-0.35*	*-0.01*	*0.06*	*-0.19*	*-0.02*	*0.06*	*-0.38*
ρ_{85}	***0.20***	*0.06*	*3.30*	***0.22***	*0.07*	*3.18*	***0.19***	*0.06*	*3.16*	***0.22***	*0.07*	*3.12*
ρ_{95}	*0.01*	*0.06*	*0.20*	*-0.08*	*0.07*	*-1.14*	*-0.01*	*0.06*	*-0.09*	*-0.09*	*0.07*	*-1.26*
ρ_{76}	***0.15***	*0.06*	*2.55*	***0.20***	*0.07*	*3.10*	***0.15***	*0.06*	*2.66*	***0.20***	*0.07*	*3.03*
ρ_{86}	***0.58***	*0.05*	*11.66*	***0.71***	*0.03*	*20.33*	***0.59***	*0.05*	*11.87*	***0.71***	*0.04*	*19.90*
ρ_{96}	***-0.26***	*0.06*	*-4.19*	***-0.31***	*0.06*	*-5.27*	***-0.28***	*0.06*	*-4.65*	***-0.29***	*0.06*	*-4.89*
ρ_{87}	***0.20***	*0.06*	*3.43*	***0.26***	*0.06*	*4.14*	***0.20***	*0.06*	*3.51*	***0.26***	*0.06*	*4.07*
ρ_{97}	*-0.11*	*0.06*	*-1.85*	***-0.15***	*0.06*	*-2.61*	*-0.10*	*0.06*	*-1.69*	***-0.15***	*0.06*	*-2.50*
ρ_{98}	***-0.18***	*0.06*	*-2.87*	***-0.41***	*0.06*	*-7.44*	***-0.18***	*0.06*	*-2.84*	***-0.39***	*0.05*	*-7.26*
θ_1	***0.04***	*0.01*	*4.80*	***0.02***	*0.01*	*4.02*	***0.04***	*0.01*	*4.94*	***0.02***	*0.01*	*4.04*
θ_2	***0.89***	*0.03*	*33.34*	***0.89***	*0.03*	*33.92*	***0.90***	*0.03*	*35.17*	***0.89***	*0.02*	*36.06*
AIC	*37.82923*			*39.6346*			*37.64409*			*39.59865*		
SIC	*38.5028*			*40.54507*			*38.31766*			*40.50911*		
LnL	*-8625.722*			*-6008.911*			*-8583.141*			*-6003.392*		

Table 5: dynamic conditional correlations—Engle (2002). $\boldsymbol{\rho_{ij}}$ is the correlation between variable i and j. (1 for France; 2- Germany; 3- Netherlands; 4- Nord Pool; 5- Spain; 6-Switzerland; 7-UK; 8- Belgium; 9: actual penetration(left two column)/planned penetration (right two columns), standard errors and p-values for the conditional correlations: AIC (Akaike Information Criterion) and SIC (Schwartz Information Criteria), LnL is the log likelihood, LR test: $\boldsymbol{\theta_1}$ =$\boldsymbol{\theta_2}$=0 (constant correlation assumption); significant values are printed in bold

	Prior to phase out			*Post phase out*			*Prior to phase out*			*Post phase out*		
	Coef.	*Std. error*	*t-value*	*Coef.*	*Std. error*	*t-value*	*Coef.*	*Std. error*	*t-value*	*Coef.*	*Std. error*	*t-value*
ρ_{21}	**0.47**	0.13	3.72	**0.85**	0.03	31.56	**0.68**	0.04	18.70	**0.84**	0.03	31.37
ρ_{31}	**0.61**	0.15	4.11	**0.86**	0.02	40.15	**0.79**	0.03	28.10	**0.86**	0.02	39.41
ρ_{41}	0.00	0.19	0.00	**0.33**	0.07	4.59	**0.28**	0.08	3.39	**0.34**	0.07	4.71
ρ_{51}	0.20	0.24	0.84	**0.26**	0.08	3.33	**0.22**	0.07	3.41	**0.25**	0.08	3.27
ρ_{61}	**0.53**	0.19	2.83	**0.71**	0.04	17.12	**0.59**	0.05	11.58	**0.71**	0.04	17.01
ρ_{71}	0.12	0.20	0.58	**0.24**	0.07	3.49	**0.21**	0.06	3.54	**0.24**	0.07	3.40
ρ_{81}	**0.84**	0.07	12.58	**0.97**	0.01	145.5	**0.99**	0.00	397.7	**0.97**	0.01	146.9
ρ_{91}	-0.06	0.15	-0.39	**-0.41**	0.06	-6.79	**-0.14**	0.07	-2.17	**-0.40**	0.06	-6.88
ρ_{32}	**0.51**	0.16	3.24	**0.89**	0.03	33.47	**0.82**	0.03	28.73	**0.89**	0.03	33.80
ρ_{42}	0.10	0.20	0.49	**0.37**	0.07	5.36	**0.39**	0.06	6.17	**0.37**	0.07	5.53
ρ_{52}	0.02	0.20	0.07	**0.22**	0.08	2.89	**0.12**	0.06	1.96	**0.22**	0.08	2.81
ρ_{62}	0.32	0.19	1.74	**0.75**	0.04	18.92	**0.54**	0.05	11.81	**0.75**	0.04	19.14
ρ_{72}	0.03	0.16	0.19	**0.22**	0.07	3.14	**0.21**	0.06	3.86	**0.21**	0.07	3.08
ρ_{82}	**0.43**	0.17	2.55	**0.85**	0.02	34.09	**0.68**	0.04	18.92	**0.85**	0.03	33.88
ρ_{92}	**-0.43**	0.12	-3.56	**-0.56**	0.05	-11.75	**-0.48**	0.05	-9.69	**-0.54**	0.05	-11.31
ρ_{43}	0.16	0.16	0.99	**0.31**	0.07	4.23	**0.35**	0.07	5.00	**0.32**	0.07	4.40
ρ_{53}	0.24	0.19	1.27	**0.17**	0.08	2.30	**0.16**	0.06	2.65	**0.17**	0.08	2.21
ρ_{63}	**0.46**	0.22	2.13	**0.73**	0.04	19.04	**0.64**	0.05	13.84	**0.73**	0.04	18.96
ρ_{73}	0.15	0.16	0.96	**0.24**	0.07	3.49	**0.25**	0.05	4.67	**0.23**	0.07	3.47
ρ_{83}	**0.71**	0.18	3.95	**0.90**	0.02	47.93	**0.80**	0.03	30.14	**0.90**	0.02	47.29
ρ_{93}	**-0.28**	0.11	-2.46	**-0.48**	0.06	-8.63	**-0.42**	0.05	-7.91	**-0.45**	0.06	-8.13
ρ_{54}	0.00	0.22	-0.02	0.10	0.07	1.53	0.00	0.07	0.04	0.11	0.07	1.59
ρ_{64}	0.05	0.14	0.38	**0.29**	0.07	3.83	**0.25**	0.07	3.70	**0.29**	0.07	3.98
ρ_{74}	0.18	0.25	0.72	0.07	0.06	1.04	**0.19**	0.06	2.99	0.07	0.06	1.05
ρ_{84}	-0.05	0.28	-0.20	**0.30**	0.07	4.07	**0.29**	0.08	3.55	**0.31**	0.07	4.23
ρ_{94}	-0.15	0.14	-1.04	**-0.29**	0.06	-4.57	**-0.20**	0.06	-3.46	**-0.30**	0.06	-4.72
ρ_{65}	0.16	0.21	0.75	**0.17**	0.08	2.19	**0.24**	0.06	3.87	**0.17**	0.08	2.19
ρ_{75}	-0.09	0.28	-0.31	0.00	0.06	-0.07	-0.02	0.06	-0.36	0.00	0.06	-0.06
ρ_{85}	0.33	0.19	1.73	0.24	0.08	3.07	**0.22**	0.07	3.36	**0.24**	0.08	3.02
ρ_{95}	0.04	0.15	0.26	-0.08	0.07	-1.18	-0.01	0.06	-0.20	-0.09	0.07	-1.26
ρ_{76}	-0.10	0.16	-0.60	**0.21**	0.07	2.97	**0.18**	0.06	2.94	**0.21**	0.07	2.91
ρ_{86}	**0.42**	0.21	2.02	**0.73**	0.04	20.09	**0.60**	0.05	11.48	**0.73**	0.04	19.89
ρ_{96}	-0.11	0.14	-0.77	**-0.31**	0.06	-4.95	**-0.25**	0.06	-3.87	**-0.29**	0.06	-4.66
ρ_{87}	0.15	0.22	0.70	**0.25**	0.07	3.62	**0.22**	0.06	3.78	**0.25**	0.07	3.58
ρ_{97}	0.06	0.17	0.35	**-0.15**	0.06	-2.28	-0.11	0.06	-1.75	**-0.14**	0.06	-2.09
ρ_{98}	-0.06	0.14	-0.42	**-0.39**	0.06	-6.40	**-0.15**	0.07	-2.18	**-0.37**	0.06	-6.29
θ_1	**0.03**	0.01	5.08	**0.05**	0.01	3.42	**0.06**	0.02	3.07	**0.05**	0.01	3.48
θ_2	**0.97**	0.01	144.30	**0.82**	0.06	12.74	**0.83**	0.07	12.49	**0.82**	0.06	13.18
AIC	38.43041			39.63043			37.96932			39.5893		
SIC	39.10398			40.54089			38.64289			40.49976		
LnL	-8763.99			-6008.27			-8657.94			-6001.96		

Table 6: dynamic conditional correlations—Tse and Tsui (2002). $\boldsymbol{\rho_{ij}}$ is the correlation between variable i and j. (1 for France; 2- Germany; 3- Netherlands; 4- Nord Pool; 5- OMEL; ; 6-Switzerland; 7-UK; 8- Belgium; 9: actual penetration (left two column)/planned penetration (right two columns), standard errors and p-values for the conditional correlations: AIC (Akaike Information Criterion) and SIC (Schwartz Information Criteria), LnL is the log likelihood, LR test: $\boldsymbol{\theta_1}$ =$\boldsymbol{\theta_2}$=0 (constant correlation assumption); significant values are printed in bold