Multinational Electricity Market Integration and Electricity Price Dynamics

Jens Lundgren[*], Jörgen Hellström[*] and Niklas Rudholm[‡]

[*]Department of Economics, Umeå University, SE-901 87 Umeå, Sweden

[‡]The Swedish Research Institute of Trade, SE -103 29 Stockholm, Sweden; and Department of Economics, Dalarna University, SE-781 88 Borlänge, Sweden.

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Abstract

The paper empirically explores the electricity price dynamics in the Nordic electricity market, Nord Pool. In particular, the focus is on determining what effect the multinational market integration, during the years 1996-2006, has had on the conditional mean electricity price, its volatility, the price jump-intensity and the price jump size. Empirically the study reveal that the conditional mean electricity price increased when Finland joined the Nord Pool exchange, and the price remained at the higher level when Denmark also joined. Turning to the price volatility, this increased when Finland joined, mainly due to an increase in jump size, and decreased when Denmark also joined Nord Pool. However, the price jump-intensity decreased both when Finland and Denmark joined the market. This means that a larger electricity market seem to reduce the probability of sudden price jumps. That is, the multinational electricity market integration in Scandinavia seems to have created a market that handle external shocks to supply and demand better than the separate national electricity market previous did.

Keywords: Electricity price, market integration, jump risk, EGARCH, Exponential Autoregressive conditional Jump Intensity.

JEL: C22, L10, L69.

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1. Introduction

Over the last 10 to 15 years electricity markets around the world has experienced rapid restructuring. Two noticeable trends are the liberalization of electricity markets and the establishment of electricity exchange markets. Another clear trend is the focus on multinational integration of different geographical electricity markets. At present the European electricity market liberalization represents the world's most extensive cross-jurisdiction reform involving integration of distinct state-level or national electricity markets (Jamasb and Pollit, 2005). Apart from in Europe restructuring processes are ongoing in a number of places around the world, e.g. in the United States, Australia and New Zeeland. In the European union, as stated in the EU Electricity Market Directives (2003/54/EG)[1], there is a clear intention of creating a single European market for electricity.

In Scandinavia, the process of electricity market integration has led to the establishment of the only multinational exchange, the Nordic power exchange, Nord Pool. The power exchange started in 1993 in Norway and has since then developed. In January 1996, the Swedish electricity market was deregulated and integrated with the Norwegian electricity market. At the same time the first multinational power exchange was created. Over the years the Nordic power exchange has grown both in terms of participants as well as concerning the amount of total trade in electricity going through the power exchange.[2] In March 1999 Finland was fully integrated, later, in March 2002 Denmark was also fully integrated with the Nordic power exchange. Apart from participants from Scandinavia traders from a large number of countries (e.g. Germany, the Netherlands, England and the United States) are actively trading at the Nord Pool today.

For the participants in electricity market trading an understanding of electricity price dynamics is crucial for risk management, portfolio management and electricity derivative pricing. An understanding of how the electricity price dynamics is affected by the ongoing process of multinational electricity market integration is therefore of great importance. In this paper, we empirically study whether the Scandinavian multinational electricity market integration has affected (and to what extent) the electricity price dynamics at the Nordic power exchange. In particular the focus is upon the effect on the conditional mean electricity price, upon the conditional variance, upon the mean jump-intensity (expected frequency of larger price movements) and on the mean jump size. The question is of particular importance in light of the commitment within Europe towards further integration of other European electricity markets. An understanding of the effects of international electricity market integration on electricity price dynamics will help both participants as well as decision makers to build better expectations about

[1] The directives may be found at http://ec.europa.eu.

[2] In 2006 over 60 percent of the electricity traded in the Nord Pool area was handled through the power exchange. The remaining part was handled through bilateral contracts.

future electricity price dynamics. To the authors knowledge this is the first empirical study of how electricity price dynamics has been affected by multinational market integration.[3]

Previous studies concerning electricity price dynamics (e.g. Pilipovic, 1998, Clewlow and Strickland, 2000, Lucia and Schwartz, 2002 and Huisman and Mahieu, 2003, Byström, 2005, Boubonnais and Meritet, 2006, and Guthrie and Videbeck, 2007) have established a number of salient features concerning electricity price dynamics: (i) Mean reversion to the long-run equilibrium price level (reflecting the marginal cost of producing electricity) exist; (ii) Large daily volatilities (compared to financial price/return series) and volatility clustering is present; (iii) Jumps (large price changes) are frequently encountered; (iv) Price series show strong seasonal patterns mainly due to the strong dependence of electricity demand on weather conditions. In order to capture these features of electricity price dynamics a mixed EGARCH-jump model is utilized in the empirical study. The conditional mean specification (excluding contributions from jumps) of the electricity price includes autoregressive components reflecting mean reversion as well as weather variables capturing seasonal effects. The time varying conditional variance component (EGARCH) captures the smooth changes in volatility and allows for volatility clustering. The jump component explains the more infrequent larger price movements. The model allows for both positive as well as negative jumps, i.e. a mean jump size (allowed to be either positive or negative) is estimated, which is important concerning electricity price modelling since large jumps are often followed by a reverse price jump (see for example Huisman and Mahieu, 2003). The GARCH-jump mixture has previously been used in mainly financial applications, e.g. Jorion (1988), Vlaar and Palm (1993) and Nieuwland, Verschoor and Wolff (1994) and an extension of the model to include a conditional autoregressive jump intensity parameter is considered by Chan and Maheu (2002). In the current empirical study, which is based on daily electricity spot price data from the Nordic power exchange covering the years 1996-2006, different specifications for the mean jump size, the conditional jump intensity and concerning the conditional variance are considered.

In summary, the results show that the conditional mean electricity price increased when Finland joined the Nord Pool exchange, and the price remained at the higher level when Denmark also joined. This can be explained by the change in the production structure toward more thermal power when these countries joined Nord Pool. Turning to the price volatility, this increased when Finland joined (mainly due to an increase in jump size) and decreased when Denmark also joined Nord Pool. When Finland joined Nord Pool, descriptive statistics show that the market was operating quite close to full capacity. As such, our interpretation of the result is that shocks in the market during

[3] However, Amundsen et al (1998) perform a simulation study predicting the effects of an integration of the Swedish, Norwegian and Finnish electricity markets.

this period more often moved the intersection between supply and demand into the steep section of the supply curve causing large price jumps.

The paper is organized as follows. Section 2 describes the relevant features of the Nordic power exchange and describes the process of multinational electricity market integration. Section 3 presents a descriptive analysis of the data used. Section 4 outlines the econometric model. Section 5 contain the empirical results while the final section discusses the empirical results.

2. Market integration in the Nordic power exchange

Since the beginning of the 1990ties, the Scandinavian power markets has evolved from separate national power markets to a multi-national power market. The restructuring process is due to a combination of national initiatives and initiatives from the European Union, whom are aiming at fully opened electricity markets by year 2007.[4] The first step towards a deregulated electricity market was taken by Norway. The Norwegian energy act in 1991 introduced competition and separated grid transmission from electricity generation. In 1992, all networks were opened for third party access but grid transmission remained a monopoly market. In 1993, a Norwegian market for power exchange opened.

In Sweden, it was not until 1996 that legislation for competition in electricity became effective. Sweden joined the Norwegian power market the same year, in what became the first international power exchange, Nord Pool. Finland joined the Nord Pool in 1998 but was not fully integrated until March 1999 when the border tariffs were removed. In 1999, the western part of Denmark joined the Nord Pool while the eastern part of Denmark joined in 2000. In practice, the Danish market was not fully integrated until 2002, when the border tariffs were removed.

The Nordic power market consist of two markets. The first market handles bilateral contracts. In this market place electricity contracts are handled and settled between two parties, a buyer and a seller, without intermediates. The second market place is the Nordic power exchange, Nord Pool. In short, Nord Pool consist of one spot market for physical contracts, Elspot, and one financial derivatives market, Eltermin, which handles futures, forwards and option contracts.[5]

The Elspot is a non-mandatory power exchange, meaning that all electricity is not exchanged in this market place. In 1996 the Elspot managed 16 percent of all electricity consumed in the Nord Pool area. Over the years the Elspot's market share has significantly increased and in 2006 over 60 percent of the total electricity consumption was

[4]For further information concerning the European electricity market directives see Directive 96/92/EC and Directive 2003/54/EC.

[5]More information regarding the market and the functioning of the Nord Pool is available at Nord Pools homepage, www.nordpool.com.

settled in this market. Since the Elspot's price function as a reference price for bilateral and financial contracts it plays an important role in the Nordic power market.

The market integration in the Nord Pool area has lead to a consolidation of different generation structures. The structure differs largely between the participating countries. For example, in 2005 hydro accounted for 99 percent of the Norwegian power generation. In the same year hydro accounted for 46 percent of the Swedish power generation. The remaining part was produced by nuclear power (45 percent) and other thermal power sources (8 percent). The generation from renewable energy sources in Sweden was less than one percent of the total generation in 2005. Thus, the generation structure is more varied in Sweden than in Norway. The Finnish generation mixture is similar to the Swedish but with more thermal power and less hydro. In 2005 the Finnish generation mixture constituted of 20 percent hydro power, 33 percent nuclear power, 47 percent other thermal power sources and 0.2 percent renewable energy. The Danish power generation consists of mainly thermal power but with a substantial part of renewable energy, primarily wind power. In 2005, 81 percent of the Danish energy was produced by thermal power and the remaining 19 percent by renewable energy sources. However, variation in precipitation between years implicate that the hydropower output in the Nord Pool area fluctuate substantially over time. This affects the generation mixture in the region and consequently the electricity flow between the participating countries, and also, the price level. The generation mixture has also been affected by the integration of new participants into the Nord Pool exchange. As discussed above the year 2005 electricity production structure differed substantially between the participating countries. These differences are consistent over time, implying that the electricity production composition in the Nord Pool area has changed when Finland and Denmark were integrated. The integration of new members has also increased the amount of electricity consumers in the area, and thus the electricity consumption. A schematic picture of the supply and demand shifts are shown in Figure 1.[6]

[Figure 1 about here.]

As can be seen in Figure 1, the intersection of supply and demand is at its lowest in the first period when only Norway and Sweden are active in the market, while the market operates quite far from it's capacity constraint. When Finland joined the market, the intersection of supply and demand is at a somewhat higher price level and also closer to the capacity constraint. This means that positive demand shocks or negative supply shocks could have a large impact on the price during this period. Finally, when Denmark

[6] Figure 1 is based on the average installed generation capacity in the participating countries for each period. The intersection of supply and demand show the average amount of electricity demand in each period. The way the figure is constructed, shifts in input prices are not considered and the price level of each production technology might therefore be slightly underestimated for period 2 and period 3.

joined Nord Pool the intersection of supply and demand are at approximately the same price level as in the period before, but further away from the capacity constraint.[7] What is also notable is that the share of hydro power in the total market has declined during the period under study. The reason is that when Finland and Denmark were integrated they brought with them a different electricity production structure, using more thermal power.

The pricing principle in the Nord Pool spot market is a single price, double auction model where the system price is set by the intersection of demand and supply bids.[8] In light of the four salient features of electricity price dynamics reported in previous literature (e.g. Pilipovic, 1998, Clewlow and Strickland, 2000, Lucia and Schwartz, 2002 and Huisman and Mahieu, 2003, Byström, 2005, Boubonnais and Meritet, 2006, and Guthrie and Videbeck, 2007), prices and price volatility is assumed to be determined as follows. First, the long-run equilibrium price level of electricity reflects the marginal cost of producing that electricity. Second, the daily volatilities and the jumps are determined by different types of exogenous changes in supply and demand. As for the changes causing normal volatility in the electricity prices, these changes can for example be normal, but unexpected, changes in temperature as compared to forecasts by the weather services. The large jumps (large price changes) are, in contrast, encountered when there are large exogenous shocks to supply or demand of electricity (e.g. large unpredicted temperature shocks, storms, production or transformation breakdowns etc).

In the empirical part of the paper, we would therefore expect that market integration has the following effects on the price, volatility and jumps. First, market integration on the Nord Pool exchange has changed the supply structure toward more expensive thermal power, especially in the case of Denmark joining Nord Pool. The restructuring of the market thus implies that there is an increased probability of thermal power being the marginal source of electricity, which would lead to higher prices as the market has became more integrated. Second, as the market becomes more integrated and increases in size both types of external shocks, affecting volatility and the jump frequency, will be less likely to have an impact on the market as a whole. As such, it is expected that

[7] Damsgaard and Green (2005) shows that after the deregulation and until the year 2000, the capacity marginal declined in the Nordic system as a whole. This implies that the electricity system will work closer to it's capacity constraint because the difference between the available production capacity and total demand of electricity decreases. After the year 2000, the capacity marginal in Sweden increased somewhat while the capacity margin continued to decrease in Finland.

[8] Several studies have studied market efficiency in the Nord Pool market. The majority of these studies have not found any proofs for price manipulation, i.e. Hjalmarsson (2000) and Amundsen and Bergman (2006). Over all, scientists seem to agree that the Nord Pool exchange have worked and works quit efficient. However, there are some studies, i.e. Johnsen et al (2000), Steen (2003) and Bask et al (2007), that have found evidence of market inefficiency at the Nord Pool exchange. In the cases where market inefficiency could not be rejected, the calculated mark ups have been small indicating that the executed market power is marginal.

the variance and jump-intensity should also decrease as the market has become more integrated.

3. Data and descriptives

The data used in the empirical study have been provided by Nord Pool and SMHI and cover the time period January 1, 1996 to February 12, 2006. All in all the sample consist of 3696 daily observations. In Figure 2 and 3 the average daily electricity prices, P_t, as stated at the Nordic power exchange and the first differences of $p_t = \log(P_t)$ are displayed.

[Figure 2 about here.]

[Figure 3 about here.]

From the figures it is evident that the price series contain a number of sharp price changes, i.e. peaks or jumps, as well as display patterns of volatility clustering. Also, positive (negative) jumps seem to be immediately followed by a reverse negative (positive) jump indicating jump reversals.[9]

Electricity prices contain seasonal patterns both in the short run (weekly patterns) and in the long run (intra yearly patterns). In order to capture short run seasonality "day of the week" dummies are used (in the empirical analysis Sunday is the reference day). Seasonality within the years is captured by including weather related variables in the regression models.[10] In Figure 4-5 the inflow of water into reservoirs and the average daily temperature are displayed.

[Figure 4 about here.]

[Figure 5 about here.]

As can be seen in the figures the variables show strong seasonal patterns. Hence, these variables should be useful in order to capture seasonality in the electricity price.[11]

[9] The Dickey-Fuller (DF) test of stationarity (random walk with drift; $\triangle p_t = c + \gamma_0 p_{t-1} + \varepsilon_t$) gives a value of -6.33 while the augmented DF test (random walk with drift; $\triangle p_t = c + \gamma_0 p_{t-1} + \sum_{j=1}^{3} \gamma_j \triangle p_{t-j} + \varepsilon_t$) gives a value of -3.93 which are both smaller than the critical value of -3.42. Thus, the logarithmic electricity price is regarded as stationary.

[10] Since the variables "inflow to reservoirs" and "temperature" are highly correlated only the former is used to capture seasonality. The time varying variance, estimated with GARCH(1,1) models, of both variables are used as explanatory variables in the regressions.

[11] Dummies indicating the summar holiday (July) and the introduction of the system with tradeble emmision rights (2005-01-01) were also included in the regression analysis but did not contribute in any significant way and were therefore excluded in the empirical study.

In Table 1 the unconditional means and standard deviations (in parenthesis) for the logarithmic electricity price as well as for the other variables for the whole period and for three subperiods are reported.

[Table 1 about here.]

The first subperiod correspond to the period 1996-01-01 to 1999-02-28 when the Nordic power exchange consisted of Norway and Sweden, the second to the period 1999-03-01 to 2002-02-28 when Finland was included, while the last subperiod correspond to the period 2002-03-01 to 2006-02-12 when Denmark had been fully integrated.[12] From Table 1 it can be noted that in period 3 the unconditional mean electricity price and the mean temperature were the highest. The unconditional mean electricity price declined (compared to period 1) during period 2 (Finland integrated with Norway and Sweden) while increased in period 3 (Denmark joined) compared with both period 1 and period 2. The standard deviations of the spot price decreased during period 2 and 3. The mean inflow of water was highest in period 2, possibly explaining the low unconditional price of electricity observed in that period.

4. Econometric model

To accommodate the salient features of electricity price dynamics a discrete time model including time-varying conditional variance and a jump component is utilized. The natural logarithm of the electricity price ($p_t = \log(P_t)$) is modelled conditional on the information set, $\phi_{t-1} = \{p_{t-1}, ..., p_1, x_{it-1}, ..., x_{i1}\}$, where x_{it} constitute covariates. The model is specified as

$$p_t = \mu_t + \varepsilon_t + J_t, \qquad (1)$$

where μ_t is the time-varying mean of the electricity price process excluding the contribution from the jump component (see equation 6), ε_t is a random disturbance term and J_t is a jump component. The stochastic innovations ε_t and J_t are assumed independent. The μ_t part is parameterized as, $\mu_t = \alpha_0 + \alpha_1 p_{t-1} + \alpha_2 p_{t-7} + \sum_{i=1}^{I} \beta_i x_{it}$, where the lagged electricity price variables captures the characteristic mean-reversion of the electricity price process (e.g., Pilipovic, 1998, Clewlow and Strickland, 2000, Lucia and Schwartz, 2002) as well as the daily seasonal pattern.[13] The vector of covariates $\mathbf{x}_t$ contain variables accounting for seasonality (discussed in the data section) as well as

[12] To capture the effect of market integration the relevant date to consider is when the markets were fully integrated. This is because the border tariffs were removed at this time and the participants meet a common price. Measuring the effect of market integration (through dummies) with official dates (before markets were fully integrated) gave qualitatively similar results.

[13] Other lag structures for μ_t were also considered. The current specification was however favoured in terms of having residuals with the lowest autocorrelation.

dummy variables to capture possible effects from multinational market integration in the conditional mean electricity price.

4.1. The jump component

The jump component in equation 1 is specified as $J_t = \sum_{k=1}^{n_t} Y_{k,t}$, where $Y_{kt} \sim NID(\theta, \delta^2)$, is the size of the k:th jump during the interval $(t-1,t)$. The jump size variable is governed by a normal distribution with mean jump size θ and variance δ^2. Compared to the specification used by Huisman and Mahieu (2003), this specification of the jump component is not constrained to only consider positive jumps. Hence, jump reversals which are common for electricity prices are possible to capture by the above specification of the jump component. The possible effect of market integration on the mean jump size is studied by letting the jump size be time varying $\theta_t = f(\mathbf{x}_t)$, where $\mathbf{x}_t$ includes dummies indicating multinational integration. Different specifications of the mean jump size are considered in the empirical application, e.g. including variation measures of weather variables.

A Poisson distribution conditional on the information set ϕ_{t-1} is assumed to describes the arrival of the integer valued number of jumps, $n_t \in \{0,1,2,...\}$, over the interval $(t-1,t)$. The conditional density of n_t is given by

$$\Pr(n_t = j|\phi_{t-1}) = \frac{\exp(-\lambda_t)\lambda_t^j}{j!}, \quad j = 0,1,2... \tag{2}$$

The expected number of jumps are given by $E[n_t|\phi_{t-1}] \equiv \lambda_t$. In order to study the effect of market integration on the expected number of jumps we follow Das (1998), Fortune (1999), Bekaert and Gray (1998) and Neely (1999) and consider a time-varying jump intensity specification by conditioning on explanatory variables. In the current case this implies specifying $\lambda_t = \exp(\boldsymbol{\beta}\mathbf{x}_t)$, where dummies for market integration are included in $\mathbf{x}_t$.[14]

4.2. Conditional variance

The random disturbance ε_t in equation 1 is assumed to be a normal i.i.d. mean-zero innovation defined as $\varepsilon_t = \sigma_t z_t$, where $z_t \sim N(0,1)$ and σ_t is assumed to follow an EGARCH(1,1) (Nelson, 1991) process.[15] In order to capture the possible effects of

[14] A specification with an autoregressive conditional jump intensity (see Chan and Maheu, 2002) was also considered in the empirical analysis. Since the extension did not contribute further it is not reported in the paper.

[15] Initially a GARCH process was utilized in line with Chan and Maheu (2002). However, due to numerical identification problems caused by the parameter restrictions imposed in the GARCH model an EGARCH model was instead chosen.

multinational market integration (through dummy variables) on the conditional variance the specification is enhanced with the explanatory variables $\sum_{k=4}^{K} \omega_k x_{kt}$. The process given by

$$\ln(\sigma_t^2) = \omega_0 + \omega_1 \xi_{1t-1} + \omega_2 \ln(\sigma_{t-1}^2) + \omega_3 \left(|\xi_{1t-1}| - \sqrt{2/\pi} \right) + \sum_{k=4}^{K} \omega_k x_{kt}, \quad (3)$$

where the normalized residual is given by $\xi_{1t} = \varepsilon_t / \sqrt{\sigma_t^2}$. The residual, ε_t, may either be defined as $\varepsilon_t = p_t - \mu_t$ or $\varepsilon_t = p_t - \mu_t - \theta_t \lambda_t$, where $E(J_t) = \theta_t \lambda_t$. The first specification of ε_t contains the expected jump component (while the second does not) and allows it to affect future volatility through the EGARCH variance factor. This specification was favoured in the empirical application.

4.3. Estimation

The conditional density of the electricity price process is a discrete mixture of distributions given by

$$\Pr(p_t|\phi_{t-1}) = \sum_{j=0}^{\infty} f(p_t|n_t = j, \phi_{t-1}) \Pr(n_t = j|\phi_{t-1}), \quad (4)$$

where

$$f(p_t|n_t = j, \phi_{t-1}) = \frac{1}{\sqrt{2\pi(\sigma^2 + j\delta_t^2)}} \times \exp\left(-\frac{(p_t - \mu_t - \theta_t j)^2}{2(\sigma^2 + j\delta_t^2)} \right), \quad (5)$$

and $\Pr(n_t = j|\phi_{t-1})$ is given by equation 2. Construction of the likelihood function may be based on the conditional density given in equation 4 noting that it involves an infinite sum over the possible number of jumps n_t. In practice the maximum number of jumps may be truncated to a large value τ, so that the probability of τ or more jumps is zero. In the empirical estimation $\tilde{\tau} > \tau$ is investigated to ensure that the likelihood and parameter estimates do not change. Maximum likelihood estimation of the models is based on equation 4.

5. Empirical study

In order to empirically study the effect of multinational market integration on electricity price dynamics a number of model specifications were tested.[16] Initially model structures with parsimonious parameterization were estimated and then successively more

[16] Throughout the different models the mean specification are the same. The specification was favoured in terms of log-likelihood and in terms of being free of autocorrelation.

elaborate specifications were considered. Estimation results for the different specifications are presented in Table A1 in the Appendix.[17] It should be emphasized that the conditional mean and conditional variance of the electricity price in the above models are given by (e.g. Chan and Maheu, 2002)

$$E(p_t|\phi_{t-1}) = \mu_t + \theta_t\lambda_t \tag{6}$$

and

$$Var(p_t|\phi_{t-1}) = \sigma_t^2 + (\delta^2 + \theta_t^2)\lambda_t. \tag{7}$$

Thus, the effect of market integration upon the conditional electricity price can either be through μ_t and/or trough θ_t and λ_t. The effect on the conditional variance similarly can be effected through σ_t^2 and/or through θ_t and λ_t. Hence, the jump component affects both the conditional mean (increasing or decreasing depending on the sign of θ_t) and the conditional variance (increasing) of the electricity price.

In Table 2 the estimation results for the model specification favoured by the Akaike information criteria is reported.

[Table 2 about here.]

The parameter estimates concerning the μ_t specification indicate that the μ_t part of the conditional mean electricity price increased (statistically significant) when Denmark joined the Nordic power exchange while there was no significant effect when Finland joined. The "day of the week" dummies are all positive (except for Saturday) in reference to Sunday. The variable inflow into water reservoirs show that higher inflows lower the conditional mean electricity price.[18]

In Table 3 the estimated values (calculated at the mean of the covariates when necessary) of the key parameters as well as standard errors calculated by the delta method are reported.

[Table 3 about here.]

As already noted, the μ_t part of the conditional mean electricity price increased when both countries joined (only statistically significant for Denmark). The jump intensity parameter λ was negatively and statistically significantly affected by the inclusion of Finland in period 2 and by the inclusion of Denmark in period 3. The jump intensity parameter λ decreased slightly from 0.110 to 0.096 during period 2 and further decreased to 0.020 in period 3. This means that the probability of at least one jump in the electricity price decreased slightly from 0.104 in period 1 to 0.091 in period 2 and

[17] The different parametrizations are reported in Table A1 in the Appendix.

[18] Models including temperature instead of inflow into reservoirs gave similar results. In these specifications higher temperatures lowered the conditional mean electricity price.

further to 0.020 in period 3.[19] For the mean jump size, θ, the estimate is close to 0 in period 1 indicating that positive and negative jumps seem to cancel out, is positive and relatively large (0.669) in period 2, and is positive and relatively smaller (0.020) in period 3. The parameter estimates for the integration dummies in the jump size function, θ_t, indicate that he mean jump size increased (statistically significant) during the period when Finland had joined (period 2), while the mean jump size decreased (statistically significant) during period 3 when Denmark had joined the Nord Pool. The time varying variance of inflow into reservoirs affect (statistically significant) both the jump intensity as well as the mean jump size negatively. Thus, the probability of jumps and the jump size are in general smaller in times of higher volatility in inflows into reservoirs. The time varying variance of temperature affects the jump intensity positively (statistically significant), while there is no significant effect on the mean jump size. This means that the probability of jumps increase in times of more volatile temperatures. For σ_t^2 the integration of Finland gave no significant effect while the inclusion of Denmark in period 3 lowered (statistically significant) σ_t^2. The time varying variance of inflow into reservoirs do not affect σ_t^2 while the time varying temperature affects it negatively.

In order to study the aggregated effect of market integration upon the conditional mean and variance of the electricity price (equation 6 and 7) these effects have been calculated and are also reported in Table 3. The overall change in the conditional mean (through changes in μ_t, θ_t, and λ_t) due to the inclusion of Finland (statistically significant)[20] was an increase of 0.078. This increase is mainly driven by the increase in the jump component of 0.064. Hence, in the period when Finland was included the conditional mean electricity price increased mainly through an (almost) unchanged probability of jumps and an increased mean jump size. Going from period 2 to period 3 there was a small increase in the conditional mean electricity price of 0.004. The small change, which is not statistically significant, is a result of two opposite forces: an increase in μ of 0.068 and a decreased contribution from jumps of -0.064. Hence, during period 3 when Denmark was included, the lowered probability of jumps and the lower mean jump size held the conditional mean electricity price down. Noteworthy is that the contribution from the jumps to the conditional mean ($\theta_t \lambda_t$) of the electricity price (given in equation 6) is close to zero in period 1 and 3 while there is a positive contribution in period 2. Referring back to Figure 3 this seem to, at least visually, correspond rather well since there is more and more pronounced spikes (jumps) during period 2. The result concerning Denmark joining Norway, Sweden and Finland in the Nord Pool electricity exchange is a slightly higher conditional mean electricity price (from 5.266 to 5.270). This was a result of a quite lowered jump intensity (λ) and a lowered mean jump size (θ), despite the higher μ. The conditional mean electricity

[19] Here, the probability of at least one jump is calculated as $1 - \Pr(n_t = 0|\phi_{t-1})$.

[20] Wald tests are used throughout the paper to test whether the conditional mean and variance of the electricity price changes over the different periods.

price, in comparison with the period with the initial assembly (Norway and Sweden), increased statistically significant when both Finland and Denmark had joined the Nord Pool.

The conditional variance of the electricity price given in equation 7 (affected by changes in σ_t^2, δ^2, θ_t, and λ_t) increased (statistically significant) in period 2 when Finland joined the Nord Pool from 0.102 to 0.144. The increase in conditional electricity price volatility is driven by an increased variance due to jumps ($[\delta^2 + \theta_t^2]\lambda_t$). The increased probability of jumps and the increased mean jump size during the period contributed by raising the conditional variance of the electricity price with 0.046 while σ^2 was almost unchanged. Going from period 2 to period 3 when Denmark joined the Nord Pool the conditional variance of the electricity price declined (statistically significant) to 0.075. This was an effect of a lowered σ^2 and a lowering of the variance contribution from jumps (close to zero) during this period. As with the conditional mean electricity price the contribution from the jumps to the conditional variance ($[\delta^2 + \theta_t^2]\lambda_t$) of the electricity price (given in equation 7) is close to zero in period 1 and 3 while there is a positive contribution in period 2. Referring back to Figure 3 this seem to, at least visually, correspond rather well since there is more and more pronounced spikes (jumps) during period 2.

6. Discussion and conclusion

In this paper, the effect of international market integration upon electricity price dynamics in the Nord Pool electricity exchange is empirically studied. The aggregated effect of market integration indicate that the conditional mean electricity price was increased significantly by the inclusion of Finland and Denmark to the Nord Pool exchange. The conditional variance of the electricity price increased when Finland joined the Nord Pool exchange. However, the increase in conditional electricity price volatility is mainly driven by an increased variance due to jumps. In contrast, the conditional variance of the electricity price declined when Denmark joined Nord Pool. This was an effect of both a lowered σ^2 and a lowering of the variance contribution from jumps during this period. Further, the price jump intensity decreased both when Finland and when Denmark joined the market.

Is there a reasonable economic interpretation of these results in terms of supply and demand in the Nordic power market? As can be seen in Figure 1 above, showing the average supply and demand in the different periods, the intersection of supply and demand is at its lowest in the first period when only Norway and Sweden are active in the market. It should also be noted that the intersection of demand and supply is quite far from the capacity constraint in the market at that time. In the second period, after Finland joined the market, the intersection of supply and demand is at a somewhat higher price level and also closer to the capacity constraint. This means that

temporary positive demand shocks or negative supply shocks will have a larger impact on the electricity price, i.e. larger jumps. Finally, after Denmark joined Nord Pool, the intersection of supply and demand are at approximately the same price level as in the period before, but somewhat further away from the capacity constraint. As such, we would expect less volatility in electricity price both due to σ^2 and due to jumps in that period. Therefore, the qualitative results from the more elaborate econometric investigation above seem to be largely confirmed by the results from a simple supply and demand analysis in the different time periods at an aggregated level. We interpret this as further support for the analysis and the results presented above.

The results in this paper can also give intuition about further European electricity market integration. The change in market structure observed in the Nord Pool area, i.e. toward more thermal power, is similar to what is expected from further European market integration. From a Scandinavian perspective this would imply that further international integration would at least not decrease the price level. From a European and a Scandinavian perspective we believe that the price volatility will be determined by how close to the capacity constraint the market will be working. The size of the price jumps will also be depending on the capacity constraint in the market. Finally, the results support our beliefs that a larger market is better in handling external shocks. This is interesting from a European perspective since an integrated European electricity market should become more stable, and external shocks in a specific area will be less likely to have an impact on the market price.

Appendix

In the appendix estimation results for the different model specifications are presented. In model 1 the conditional mean jump intensity (λ), the mean jump size (θ) and the variance (σ^2) are assumed to be constant over the full period while μ_t is allowed to be affected by the multinational market integration through dummies. In model 2 the variance, σ^2 is allowed to differ over the different subperiods (but constant within the subperiod) while the jump components, λ and θ are assumed constant over the full period. In model 3 the jump components (λ_t, θ_t) are allowed to differ during the different subperiods while keeping the variance, σ^2, constant over the full period. In model 4 both the variance σ_t^2 as well as the jump components (λ_t and θ_t) are allowed to differ over the different subperiods. In model 5 an EGARCH specification is considered for the conditional variance, σ_t^2, while the jump components are specified as in model 4. Model 6 extends model 5 by including variables controlling for weather variations (time-varying volatility in inflow of water to reservoirs and in temperature predicted by a GARCH(1,1) model) in the conditional variance, the jump intensity as well as in the jump size specification for the electricity price.

[Table A1]

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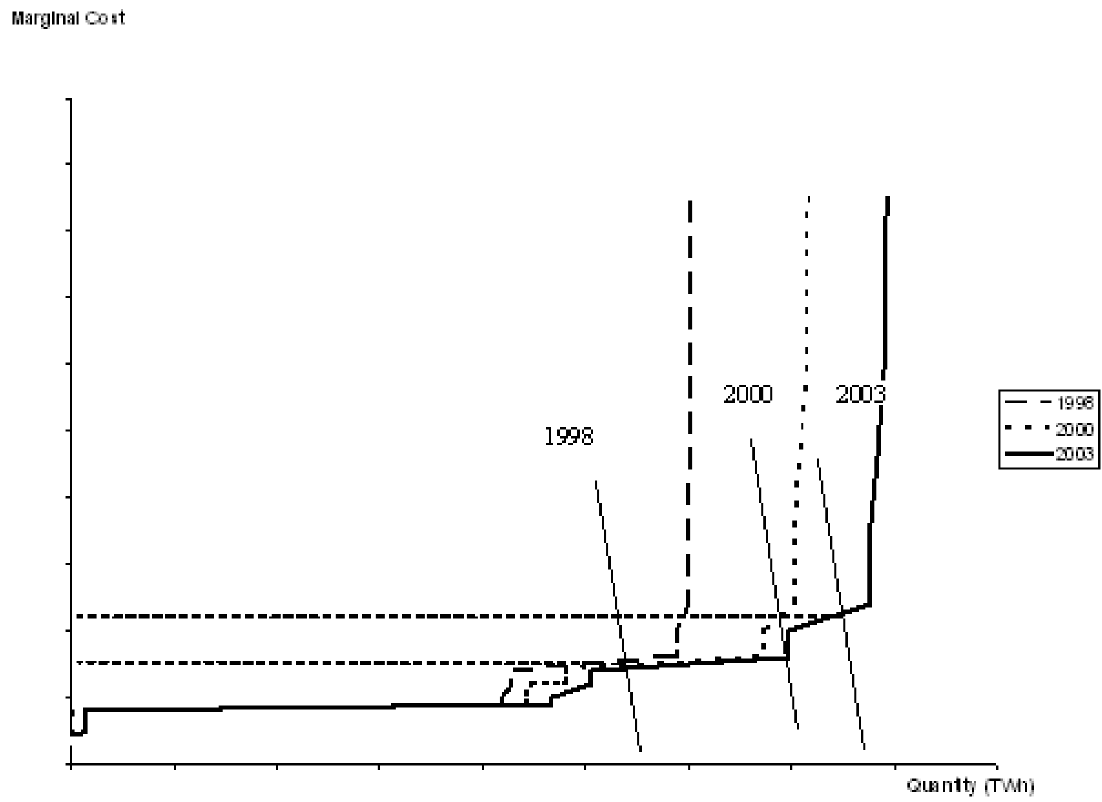

Figure 1: Electricity supply and demand.

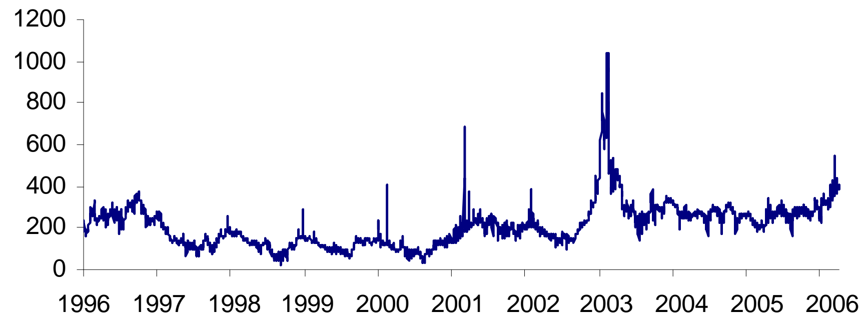

Figure 2: Daily electricity prices (P_t) at NordPool.

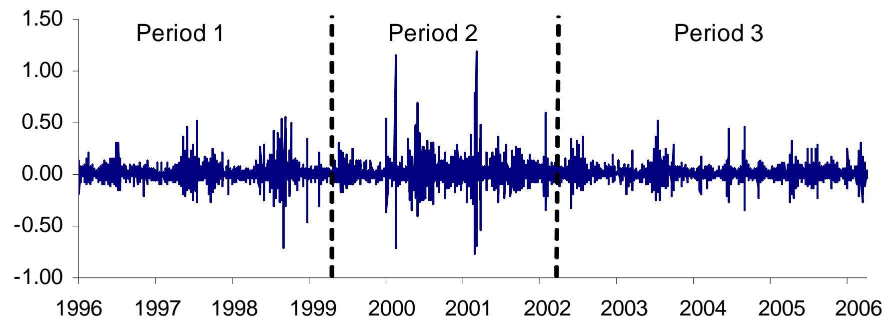

Figure 3: First differences of $\log(P_t)$.

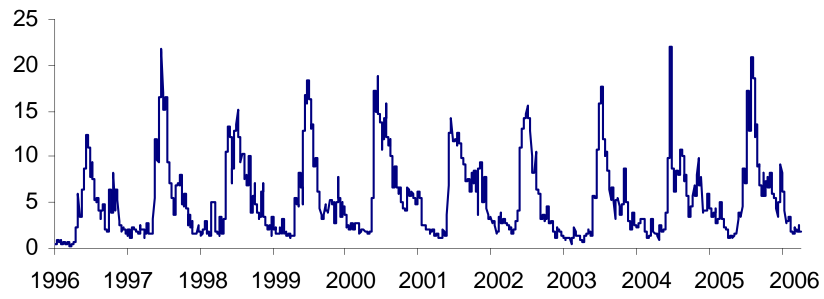

Figure 4: Inflow of water to reservoirs (MWh).

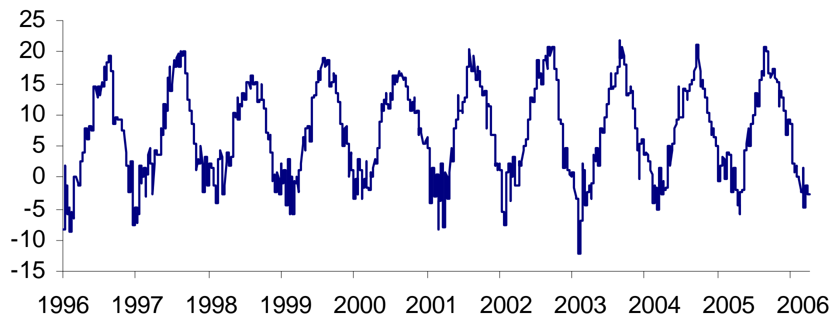

Figure 5: Average daily temperature.

Table 1: Descriptive statistics.

	Period 1	Period 2	Period 3	Whole period
p_t	5.075	4.929	5.597	5.236
	(0.442)	(0.421)	(0.322)	(0.490)
Inflow (MWh)	478514	606411	534034	537330
	(408159)	(430485)	(423976)	(424063)
Variance (Inflow)*	0.266	0.375	0.314	0.317
	(0.547)	(0.606)	(0.627)	(0.598)
Temperature (C^0)	6.124	7.360	7.536	7.015
	(7.338)	(7.161)	(7.519)	(7.406)
Variance (Temp.)*	0.589	0.538	0.591	0.575
	(0.560)	(0.503)	(0.554)	(0.542)
Nr. of observations	1155	1096	1445	3696

*Time varying conditional variance estimated with GARCH(1,1)

Table 2: Estimation results.

Jump components:

$\ln(\lambda_t) = \gamma_0+\gamma_1\text{dFin}+\gamma_2\text{dDen}+\gamma_3\sigma^2_{Inflow}+\gamma_4\sigma^2_{Temp}$

$\theta_t = \theta_0+\theta_1\text{dFin}+\theta_2\text{dDen}+\theta_3\sigma^2_{Inflow}+\theta_4\sigma^2_{Temp}$

Conditional variance:

$\ln(\sigma^2_t) = \omega_0+\omega_1\xi_{1t-1}+\omega_2\ln(\sigma^2_{t-1})+\omega_3(|\xi_{1t-1}| - \sqrt{2/\pi}) + \omega_4\text{dFin}+\omega_5\text{dDen}+$
$\omega_6\sigma^2_{Inflow}+\omega_7\sigma^2_{Temp}$

Variable	Estimate	s.d.	Variable	Estimate	s.d.	Variable	Estimate	s.d.
Constant	0.343*	(0.016)	γ_0	-2.324*	(0.016)	ω_0	-2.253*	(0.017)
p_{t-1}	0.721*	(0.012)	γ_1(dFin)	-0.133*	(0.015)	ω_1	-0.067*	(0.016)
p_{t-7}	0.199*	(0.012)	γ_2(dDen)	-1.353*	(0.023)	ω_2	0.048*	(0.017)
dMon	0.206*	(0.017)	γ_3	-1.965*	(0.034)	ω_3	0.208*	(0.015)
dTues	0.122*	(0.017)	γ_4	1.284*	(0.017)	ω_4 (dFin)	-0.009	(0.018)
dWed	0.038*	(0.016)	θ_0	0.114*	(0.018)	ω_5 (dDen)	-0.275*	(0.016)
dThur	0.084*	(0.016)	θ_1 (dFin)	0.673*	(0.018)	ω_6	0.019	(0.017)
dFri	0.071*	(0.017)	θ_2 (dDen)	-0.649*	(0.019)	ω_7	-0.114*	(0.019)
dSat	-0.009	(0.017)	θ_3	-0.385*	(0.075)			
Inflow	-0.080*	(0.017)	θ_4	0.008	(0.017)			
dFin	0.013	(0.016)	δ^2	0.026*	(0.002)			
dDen	0.068*	(0.015)						
Log-likelihood	-26,782							
AIC	53,626							

* Significant at the 5 percent level. dFin and dDen are the dummies for market integration.

Table 3: Parameter estimates for key variables*

	Period 1	Period 2	Period 3
μ	5.188	5.201	5.269
	(0.008)	(0.008)	(0.008)
λ	0.110	0.096	0.020
	(0.001)	(0.001)	(0.001)
θ	-0.000	0.669	0.020
	(0.001)	(0.001)	(0.001)
σ^2	0.099	0.098	0.075
	(0.001)	(0.001)	(0.001)
$E(p_t\|\phi_{t-1})$	5.188	5.266	5.270
	(0.008)	(0.008)	(0.008)
$Var(p_t\|\phi_{t-1})$	0.102	0.144	0.075
	(0.002)	(0.005)	(0.002)

*Standard errors calculated with the delta method in paranthesis

Table A1: Estimation results for the different model specificantions.

	Model 1		Model 2		Model 3		Model 4	
	Estimate	s.d.	Estimate	s.d.	Estimate	s.d.	Estimate	s.d.
Constant	0.254*	(0.027)	0.210*	(0.034)	0.310*	(0.018)	0.248*	(0.019)
p_{t-1}	0.731*	(0.018)	0.734*	(0.017)	0.714*	(0.031)	0.729*	(0.089)
p_{t-7}	0.208*	(0.012)	0.211*	(0.013)	0.217*	(0.028)	0.211*	(0.012)
dMon	0.210*	(0.017)	0.208*	(0.021)	0.196*	(0.034)	0.215*	(0.021)
dTues	0.100*	(0.016)	0.099*	(0.033)	0.093*	(0.041)	0.114*	(0.016)
dWed	0.030	(0.020)	0.043*	(0.020)	0.031	(0.033)	0.047*	(0.017)
dThur	0.071*	(0.023)	0.064*	(0.026)	0.058	(0.040)	0.074*	(0.017)
dFri	0.063*	(0.016)	0.076*	(0.035)	0.057*	(0.028)	0.087*	(0.016)
dSat	-0.016	(0.015)	-0.013	(0.037)	-0.022	(0.037)	-0.007	(0.015)
Inflow	-0.069*	(0.015)	-0.064*	(0.019)	-0.074*	(0.019)	-0.066*	(0.014)
dFin	0.016	(0.016)	0.017	(0.014)	0.001	(0.030)	0.000	(0.016)
dDen	0.050*	(0.016)	0.042*	(0.016)	0.058*	(0.029)	0.051*	(0.019)
Jump components: $\ln(\lambda_t) = \gamma_0 + \gamma_1$dFin+$\gamma_2$dDen, $\theta_t = \theta_0 + \theta_1$dFin+$\theta_2$dDen								
γ_0	-2.874*	(0.023)	-2.856*	(0.021)	-2.797*	(0.045)	-2.750*	(0.038)
γ_1 (dFin)					0.127	(0.018)	-0.151*	(0.018)
γ_2 (dDen)					-1.044*	(0.017)	-0.995*	(0.017)
θ_0	0.586*	(0.063)	0.598*	(0.092)	-0.594	(0.017)	-0.345*	(0.017)
θ_1 (dFin)					1.417*	(0.041)	1.187*	(0.068)
θ_2 (dDen)					-0.389*	(0.015)	-0.550*	(0.017)
δ^2	0.104*	(0.016)	0.102*	(0.012)	0.058*	(0.014)	0.055*	(0.007)
Conditional variance: $\ln(\sigma^2) = h_0 + h_1$dFin+$h_2$dDen								
h_0	-2.363*	(0.24)	-2.358*	(0.280)	-2.420*	(0.061)	-2.365*	(0.170)
h_1 (dFin)			0.071	(0.084)			0.041*	(0.016)
h_2 (dDen)			-0.376	(0.331)			-0.282*	(0.019)
Log-likelihood	-31,961		-31,284		-30,451		-29,969	
AIC	63,954		62,604		60,942		59,982	

* Significant at the 5 percent level. dFin and dDen are the dummies for market integration.

Table A1: continued.

	Model 5		Model 6	
	Estimate	s.d.	Estimate	s.d.
dFin	0.010	(0.017)	0.013	(0.016)
dDen	0.048*	(0.016)	0.068*	(0.015)
Jump components: $\ln(\lambda_t) = \gamma_0 + \gamma_1 \text{dFin} + \gamma_2 \text{dDen} + \gamma_3 \sigma^2_{Inflow} + \gamma_4 \sigma^2_{Temp}$ $\theta_t = \theta_0 + \theta_1 dFin + \theta_2 dDen + \theta_3 \sigma^2_{Inflow} + \theta_4 \sigma^2_{Temp}$				
γ_0	-2.709*	(0.018)	-2.324*	(0.016)
γ_1(dFin)	-0.628*	(0.096)	-0.133*	(0.015)
γ_2(dDen)	-0.539*	(0.023)	-1.353*	(0.023)
γ_3			-1.965*	(0.034)
γ_4			1.284*	(0.017)
θ_0	0.236*	(0.034)	0.114*	(0.018)
θ_1 (dFin)	0.467*	(0.024)	0.673*	(0.018)
θ_2 (dDen)	-0.062*	(0.016)	-0.649*	(0.019)
θ_3			-0.385*	(0.075)
θ_4			0.008	(0.017)
δ^2	0.296	(0.039)	0.026*	(0.002)
Conditional variance: $\ln(\sigma^2_t) = \omega_0 + \omega_1 \xi_{1t-1} + \omega_2 \ln(\sigma^2_{t-1}) + \omega_3(\lvert\xi_{1t-1}\rvert - \sqrt{2/\pi})$ $+ \omega_4 \text{dFin} + \omega_5 \text{dDen} + \omega_6 \sigma^2_{Inflow} + \omega_7 \sigma^2_{Temp}$				
ω_0	-2.453*	(0.016)	-2.253*	(0.017)
ω_1	-0.077*	(0.017)	-0.067*	(0.016)
ω_2	-0.013	(0.018)	0.048*	(0.017)
ω_3	0.070*	(0.017)	0.208*	(0.015)
ω_4 (dFin)	0.269*	(0.020)	-0.009	(0.018)
ω_5 (dDen)	-0.477*	(0.028)	-0.275*	(0.016)
ω_6			0.019	(0.017)
ω_7			-0.114*	(0.019)
Log-likelihood	-29,062		-26,782	
AIC	58,174		53,626	

* Significant at the 5 percent level.