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Energy Sustainability

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ABSTRACT: The power system has to deal with three main sources of uncertainty: demand uncertainty and load prediction errors, failure of power plants and uncertainty of wind. The growing share of wind and other intermittent generation sources in the European supply increases the uncertainty about power production in day-ahead and longer-term predictions. As EU member states increase the deployment of wind power and other intermittent renewable energy sources, the intraday and balancing market will gain more interest, as additional demand for reserve and response operations is needed. Hence, it becomes relevant to analyse the effect of wind power forecasting errors on intraday power prices. A higher forecast error will increase the need of intraday markets to balance out the oversupply or deficit of wind power on an hourly basis. This oversupply or deficit can be corrected though flexible hydropower plants; however the power price is highly influenced by the fluctuations in the reservoir level (Huisman et. al [2013]). In this paper, we question to what extent hydropower a stabilizing effect has on the impact of wind forecast errors on NordPool intraday prices. To do so, we examine the peak and off peak imbalance power prices for the Scandinavian market (ELBAS) from 2011 until 2013 with a Markov regime-switching model in periods with low and high hydro reservoir levels. Results indicate that under wind forecast error, the use of hydropower capacity in intraday markets is proven to be an effective volatility control mechanism. However, the price stabilizing effect of hydropower capacity does not take place at all times.

JEL Codes: L11, Q41, C24

Keywords: Electricity, intraday prices, wind forecast error, Markov-switching models

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1 Introduction

The European Unions aim of increasing the share of energy from renewable sources introduced great changes in Europe on the electricity supply side. More electricity is being generated by intermittent renewable energy sources as in photovoltaic and wind. This introduced next to demand uncertainty, load prediction errors and failure of power plants, a new source of uncertainty, the uncertainty of renewable power production. This caused the power system to deal with three main sources of uncertainty. Especially the growing share of wind and other intermittent generation sources in the European supply decreases the accuracy of day-ahead and longer-term predictions on power production. As EU member states increase the deployment of wind power and other intermittent renewable energy sources, the intraday and balancing markets will gain more interest as additional demand for reserve and response operations is needed.

Firstly wind energy integration into electricity markets creates challenges on: support scheme design, strategic behaviour in the presence of large-scale wind energy and, new methods for assessing the economic value of wind power (Glachant and Finon [2010]). The effect of intermittent resources on wholesale power prices is already been analyzed by many authors (Gelabert et. al [2011]; Sáenz de Miera et. al [2008]; Forrest and MacGill [2013]; Würzburg et. al [2013]; Mulder and Scholtens [2013]; Costa-Campi and Trujillo-Baute [2014]). They conclude that renewable resources produce lower wholesale market clearing prices. This implies that an increase in wind proportion (and other renewables) will have a price suppressing effect. This results essentially from low variable costs and supporting incentives such as fixed feed-in tariffs and premium.

Next to the price suppressing effect, the high volatility of wind power generation will result in more volatile day-ahead prices (Jacobsen and Zvingilaite [2010]; Green and Vasilakos [2010]; Woo et. al [2011]). These variations in generated wind power affects the operation of the power system on a daily basis leading to higher balancing costs and greater fluctuation in the reserve requirements. One way to reduce the necessity of reserves is reducing scheduling intervals (Pérez-Arriaga and Batlle [2012]). In this regard intraday markets provide the possibility to adjust previous positions in day-ahead markets and are closer to real time balancing markets. Day-ahead wind prediction errors, for instance in Germany, represent more than 20 percent of the average power production (Weber [2010]), and the wind power forecasting errors decrease only when the forecasting horizon is reduced. Therefore, in a system with a well functioning intraday market, the effects from the forecasting errors of wind power are (partially) transferred from the reserve requirements and balancing cost to the intraday market price. Hence, it becomes relevant to analyze the effect of wind power forecasting errors on intraday prices.

Supply side uncertainties are a decisive part of the power system, along with market design mechanisms (as intraday or balancing markets) the power system needs means of flexibility to address this uncertainty. Hydro power plants are highly flexible[1], however the power price de-

[1]Hydro power plants have the technical capacity to provide a full start within 15 minutes.

pending on the marginal production cost of hydropower is greatly influenced by the fluctuations in the reservoir level. Huisman et. al [2013] state that the value of the option to store water is high when reservoir levels are low (hydro has a marginal cost-convenience yield or opportunity cost). The value of the option to store water is low when reservoir levels are high (hydro has low or zero marginal cost). Therefore, hydro reservoir levels determine the opportunity cost of hydropower generators, ultimately setting their incentives to produce electricity, and consequently to provide flexibility to the power system.

The complementarity between wind and hydropower is analyzed in a day-ahead market context by Green and Vasilakos [2010] and Mauritzen [2013]. Green and Vasilakos [2010], use Danish data to estimate, taking into account transmission capacity, the short-run effect of wind power production on local prices. The authors find a high short-run correlation between wind power and net power exports. At a daily level they note that Denmark exports during off-peak and argue that this is evidence for the storage of Danish windpower in the hydropower magazines of their neighboring countries. Following a similar approach, Mauritzen [2013] states that wind-hydropower interaction has an effect on the international exchange between Denmark and Norway. The author concludes that 40 percent of wind power produced in Denmark is stored in Norwegian hydropower basins, therefore hydropower can act as a battery until a certain extent.

In an efficient intraday market, forecasting errors of wind power should be translated to prices and balanced through flexible hydropower, however the water level in the hydro reservoir determines the strength of this relation. In this paper, we question to what extent hydro power has a stabilizing effect on the impact of wind forecasting errors on intraday prices. To do so, we examine the hourly intraday power prices for the NordPool market (ELBAS, Volume weighted average price per MWh) from 2011 until 2013. According to Table 1 approximately 50 percent of the total generation capacity in the NordPool market depends on hydro and 30 percent on nuclear and other thermal power. Wind accounts for 9 percent of the total generation capacity. The Scandinavian market provides an outstanding setting for this research. The intermittent wind generation is combined with large hydro generation capacity in a single and mature regional market.

Table 1: Nordic generation capacity by power source (2012)(MW)

Nuclear	12095
Other thermal	30025
Hydro	50076
Wind	8898
Photovoltaic	24

In order to identify the stabilizing effect of hydro power, corresponding with the hydro reservoir level, on the intraday power price under wind forecast errors, a Markov regime-switching model is employed. Positive and negative wind forecast errors will induce the wind power producer to make up for the deficit or sell the excess on the Elbas market to reduce the costs they incur on the balancing market. However due to the difference in opportunity costs of hydropower generators, depending on the level of water in hydropower basins, the use of this flexibility to decrease or increase power production is also priced differently. We expect that the extent to which hydropower has a stabilizing effect on the intraday power prices with wind forecast errors will differ in times of high and low levels in hydro capacity. Our results show a clear difference between peak and off peak ELBAS hourly prices. The use of hydro power capacity is an effective mechanism to control the volatility, which emerges from wind forecast errors (excess and deficit) in intraday markets. However, an important part of the price stabilizing effect of the hydropower takes place during the off peak hours.

The paper proceeds as follows. Section 2 discusses the methodology that we apply. Section 3 summarises the data we use. Section 4 presents the results and Section 5 concludes.

2 Methodology

In this section the dynamics of the intraday electricity prices in the NordPool market are being captured with a regime switching model. Regime-switching models offer the possibility to introduce various mean reversion rates and volatilities depending on the state of the system. This approach is flexible enough to be used in modeling electricity prices dynamics in order to distinguish the state in which the prices behave more stable from the state in which the price behavior is more turbulent. The regime-switching model is used for modeling price abnormalities and is derived by gradually extending the basic mean-reverting specification to include these (Lucia and Schwartz [2002]).

The first regime switching model is a basic model, which serves as a benchmark for the second model. The second model extends the first model by including the deviation between realized and forecasted wind related to the hydro reservoir levels, to influence the transition probabilities between the states.

2.1 Model 1: a two regime-switching model for intraday electricity prices.

Let s(t) be the natural logarithm of the intraday price for delivery of 1 MW during hour t. The intraday price is assumed to be the sum of a deterministic component $d(t)$ and a stochastic component $x(t)$. $d(t)$ is a highly predictable component accounting for the seasonality effects and x(t) is the random component reflecting unpredictable movements of the prices (Hamilton [1994]). The construction of the models is based on Huisman and Mahieu [2003], Mount et. al [2006] and Huisman [2008].

$$s_t = d_t + x_t \tag{1}$$

The deterministic component consists of a mean price level μ_1 and allows for a different price during weekend delivery reflected by β. The parameter β is expected to be negative as weekend days normally exhibit lower prices than working days. $\omega(t)$ is the weekend dummy variable which incorporates seasonality in the estimation process and is 1 if t is on a weekend day and 0 if it is on any other day:

$$d_t = \mu_1 + \beta_1 \omega_t \tag{2}$$

The stochastic component in the normal regime consists of a mean reversion component with speed of mean reversion α and the error term in state 1 $\epsilon_{1,t}$ is assumed to be standard normally distributed multiplied with σ_1 that represents the standard deviation of the error term. The mean reverting stochastic component then equals:

$$x_t = (1 - \alpha)x_{t-1} + \sigma_1 \epsilon_{1,t} \quad | \quad S_t = 1 \tag{3}$$

The stochastic component in the second state, represents the intraday price under non normal market conditions such as a sudden increase or decrease on the demand or supply side of electricity. This could result in an increase or decrease of the price. In this state the stochastic component is modeled as a random price shock mean price level μ_2, which is the increase or decrease in the price level. $\epsilon_{2,t}$ is a normally (0,1) distributed error term multiplied with the standard deviation of the electricity price in state 2, σ_2:

$$x_t = \mu_2 + \sigma_2 \epsilon_{2,t} \quad | \quad S_t = 2 \tag{4}$$

Let S_t be the state in which the electricity market is during hour t ($S_t = 1, 2$). S_t is assumed to follow a Markov chain that switches between the two states with constant transition probabilities. The element $p_{i,j}$ denotes the conditional probability that the process is in state i at time t given that the process was in state j at time $t - 1$: $p_{i,j} = Pr\{S_t = i | S_{t-1} = j\}$. Hence, $p_{1,1}$ is the probability that the electricity market was in state 1 and remains in state 1 the following hour and $p_{2,1} = 1 - p_{1,1}$ is the probability that the electricity market was in state 1 and switches to state 2 the following hour. Logistic transformation ensures that the estimated probabilities are between 0 and 1. The value $p_{i,i}$ can be interpreted as the actual transition probability.

$$p_{i,i} = \frac{1}{1 + e^{-\lambda_i}} \tag{5}$$

2.2 Model 2: a two regime-switching model with wind forecast error dependent transition probabilities

In model 2 the transition probabilities for the regime-switching model are assumed to be depending on the wind forecast errors. In this model wind affects the probability of spikes through the forecasting error, which is the deviation between actual ($rwnd_t$) and forecasted wind ($fwnd_t$) levels. A higher forecast error will increase the need of the use of intraday markets to balance out the oversupply or deficit of wind on hourly basis. This oversupply or deficit can be corrected through highly flexible hydro power plants. Huisman et. al [2013] argue that the marginal costs of hydro production varies depending on reservoir levels that determine the hydro production capacity. The authors state that higher reservoir levels, more hydro capacity, leads to significant lower power prices and lower reservoir levels lead to higher power prices due to the marginal opportunity costs of the option to delay production. Therefore in this model we distinguish between high hydro reservoir levels, where this flexibility has low marginal production cost and price and low hydro reservoir levels for which the marginal production cost are certainly higher.

$$p_{i,i} = \lambda_i + \kappa_i^{hp}(rwnd_t - fwnd_t)I_t^h I_t^p + \kappa_i^{hn}(rwnd_t - fwnd_t)I_t^h I_t^n + \\ \kappa_i^{lp}(rwnd_t - fwnd_t)I_t^l I_t^p + \kappa_i^{ln}(rwnd_t - fwnd_t)I_t^l I_t^n \quad (6)$$

In line with **??** we take into account the asymmetric effects of positive and negative forecast errors. To capture the effect of positive and negative wind deviations, in periods of high and low hydro reservoir levels, on the transition probability we included dummy variables into the model. For the high hydro reservoir level we include a dummy variable I_t^h that takes on the value of one when t is an hour with a hydro level higher or equal to 61.4%, which is the average hydro reservoir level[2] in the analysed period. For the low hydro reservoir level we include a dummy variable I_t^l that takes on the value of one when t is an hour with a hydro level lower than 61.4% and zero elsewhere. Let I_t^p be a dummy variable that takes on the value of one when t is an hour with wind excess, the realized volume of wind power is higher than the forecasted volume of power generated with wind, and zero elsewhere. Let I_t^n be a dummy variable that takes on the value of one when t is an hour with a wind deficit, which means that the realized volume of wind power is lower than the forecasted volume of wind power and zero elsewhere. Hence, κ_i^{hp} and κ_i^{hn} captures the effect of positive and negative forecasting errors on the transition probability during high hydro level and κ_i^{lp} and κ_i^{ln} captures the effect of positive and negative forecasting errors during periods of low hydro level.

The parameters (μ_1, β, α, σ_1, μ_2, σ_2, $\lambda(1)$, $\lambda(2)$, κ_1^{hp}, κ_2^{hp}, κ_1^{hn}, κ_2^{hn}, κ_1^{lp}, κ_2^{lp}, κ_1^{ln}, κ_2^{ln}) of the two regimes switching model are estimated using maximum likelihood.

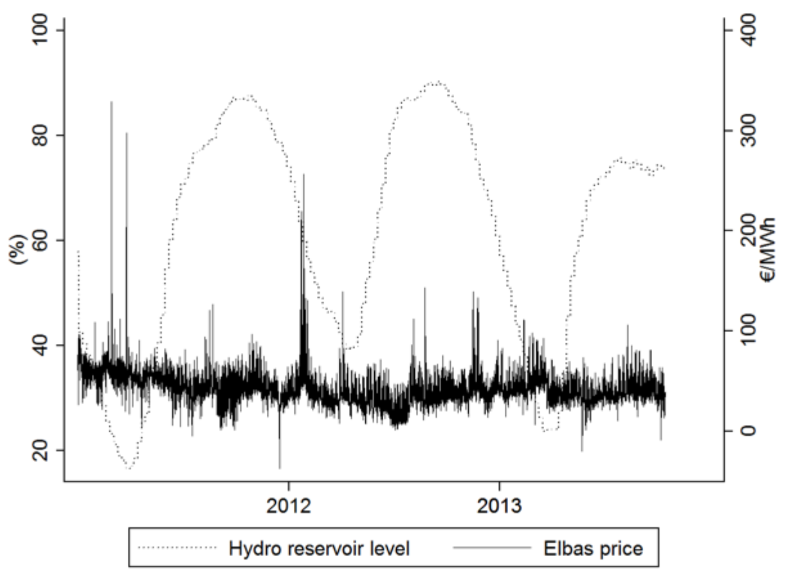
3 Data

The primary data for this study consists of hourly intraday electricity prices for the NordPool market (ELBAS), which is the single power market for Norway, Sweden, Finland, Denmark and since 10 December 2013 also includes Estonia and Lithuania. The Elbas is a continuous market, and trading takes place every day around the clock until one hour before delivery. Elbas also covers a larger intraday market than local balancing markets. The liquidity in the Nordic intraday power market is analyzed by Weber [2010]. According to the author liquidity plays a crucial role in determining the correct value of the asset as with high liquidity transactions in the asset will not significantly affect its value and result will only in transaction costs for the bidder. Also

[2] This analysis is also conducted with the first quantile and fifth quantile as the selection criteria for high and low hydro reservoir levels. From these results a similar conclusion can be drawn and are avaliable upon request.

sufficient liquidity is essential for the efficient use of production resources through trading. In 2011, 2012 and 2013 the turnover on Elbas was 2.7 TWh, 3.2 TWh and 4.2 TWh, respectively.[3] This corresponds to 0.7 percent in 2011, 0.8 percent in 2012 and 1.1 percent in 2013 of the total electricity consumed in the Nordic market. The percentage and therefore the liquidity has risen between 2011 and 2013. The price series range from January 1th, 2011 until November 10th, 2013, having 12490 hourly volume weighted average price observations (€/MWh). For the analysis we distinguish between peak[4] and off peak prices[5], because they differ in level of power demand. In general during off peak hours power demand will be lower than during peak hours. The hourly estimated amount of wind power generation in Denmark is sent in at 17:00 CET, one day prior to actual realization. This data and the hourly actual realized wind power production (MWh) is obtained from the Danish national transmission system operator [6]. The data for the weekly hydro reservoir level for electrical exchange in percentage of total reservoir capacity is obtained from Nordpoolspot. The intraday prices and hydro reservoir level in percentage are represented in Figure 1 and the descriptive statistics are reported in Table 2.

Figure 1: ELBAS prices and hydro reservoir level



According to literature [7] electricity prices exhibit seasonality, mean-reversion, time-varying volatility and price spikes. Firstly from Figure 1 it is obvious that mean reversion is present in the intraday prices. In the long run electricity prices are expected to revert to the marginal production costs and therefore will tend to be around its mean. Positive and negative price spikes

[3] www.nordpoolspot.com

[4] Equally weighted average over the intraday prices from 8am to 8pm.

[5] Equally weighted average over the intraday prices from 8pm to 8am.

[6] www.energienet.dk and www.nordpoolspot.com

[7] For an overview of the characteristics of electricity price dynamics and a summary of the literature we refer to Eydeland and Wolyniec [2003], Pilipovic [2007], and Huisman [2009].

are also present in the intraday prices. High volatility is another stylized fact that can be seen from Figure 1. The hydro reservoir level suffers from seasonal fluctuations with high levels in the summer time and low levels during the winter.

Table 2: Descriptive statistics.

Price- Total hydro	**Peak**	**Off peak**
Mean	47.733	43.368
Min.	4.590	0.740
Max.	329.320	297.880
Std. dev.	15.134	14.029
Price- High hydro	**Peak**	**Off peak**
Mean	45.359	35.445
Min.	4.590	0.740
Max.	211.230	219.710
Std. dev.	13.547	11.892
Price- Low hydro	**Peak**	**Off peak**
Mean	50.785	43.536
Min.	9.220	3.490
Max.	329.320	297.880
Std. dev.	16.463	15.205
FE- **Total hydro**	**Peak**	**Off peak**
Mean	100.739	64.343
Min.	-2003.800	-2007.900
Max.	1383.300	2675.000
Std. dev.	285.205	257.519
FE- **High hydro**	**Peak**	**Off peak**
Mean	75.338	40.685
Min.	-2003.800	-2007.900
Max.	1383.300	2675.000
Std. dev.	274.801	238.362
FE- **Low hydro**	**Peak**	**Off peak**
Mean	133.391	94.730
Min.	-1029.700	-1005.300
Max.	1273.500	1355.300
Std. dev.	294.875	277.285

Notes: Descriptive statistics for hourly peak and off peak load electricity ELBAS intraday prices for the period of January 1, 2011 to November 9, 2013. The number of observations for base, peak and off peak are respectively, 24933, 12443 and 12490. The forecast error $FE = R_{wnd} - F_{wnd}$

The descriptive statistics of the ELBAS intraday prices and wind forecast error are reported in Table 2. We observe that in times of low hydro reservoir level the mean of the forecast error has the highest value, however the coefficient of variance (std. dev. / mean) is 4.44 and 2.51 during high and low hydro reservoir levels, respectively. Hence, the dispersion of the wind forecast error is considerably higher during the high hydro reservoir level. According to expectation a higher unpredictability of wind should have an increasing effect on the price volatility. Intraday prices have a higher standard deviation in times of low hydro reservoir level, but the coefficient of variance is 0.3 in both cases. Hence, taking into account the differences in the mean price level between high and low levels of water inventory their dispersion is similar during both periods. This simple statistical feature can be seen as a first sign of the price stabilizing effect of hydro reservoir levels under wind forecasting errors. In addition, it also identifies different patterns between peak and off peak hours. During high hydro reservoir levels only off peak hours show a higher dispersion of the wind forecast error. Low hydro reservoir levels show that the dispersion of the wind forecast error is equal for peak and off peak hours. Besides, on average, the highest intraday prices take place during peak hours in times of low level of water inventory and the lowest during off peak hours with high level of hydro. Therefore, on the intraday market the difference between peak and off peak hours can be explained by the fact that the transmission system is more constrained during peak than during off peak hours, which is in line with previous studies on the day-ahead market (Green and Vasilakos [2010] and Mauritzen [2013]). According to these statistics and given the regional nature of the NordPool market, it is expected that a substantial part of the price stabilizing effect of hydro reservoir levels takes place during off peak hours.

4 Results

Table 3: Parameter estimates for regime switching model 1

	Off peak		Peak	
μ_1	3.5599*	(0.0216)	3.8636*	(0.0147)
μ_2	-0.2101*	(0.0355)	-0.0787*	(0.0227)
β_1	-0.0163**	(0.0079)	-0.1681*	(0.0071)
α	0.0593*	(0.0039)	0.0588*	(0.0032)
λ_1	3.0249*	(0.0715)	2.7545*	(0.0628)
λ_2	0.2969*	(0.0878)	-0.3698*	(0.0938)
σ_1	0.1176*	(0.0014)	0.0843*	(0.0009)
σ_2	0.7135*	(0.0174)	0.4811*	(0.0125)
$p1,1$	0.9537		0.9402	
$p2,2$	0.5737		0.4086	

Notes: Standard errors are in parenthesis.* and **, denote a test statistic is statistically significant at the 1% and 5% level of significance, respectively.

In Table 3 we observe the parameter estimates of the Markov regime switching model with a constant transition probability (model 1) and in Table 4 the parameter estimates of the Markov regime switching model with transition probabilities depending on wind forecast errors and hydro reservoir levels (model 2) are given. Firstly analyzing the results from model one we observe that μ_1, which is the mean price level in the first state is higher than the mean price level in the second state, due to a negative μ_2. Meaning that in the second state the mean log price tends to be lower than the mean level during the first state and shows downward price spikes. The model distinguishes the regimes in terms of volatility. The volatility of the intraday price in the first state (σ_1) is lower than the volatility in the second state (σ_2). This states that the downward movement in prices are more volatile than the upward movements. With respect to β_1 we expect this to be negative as weekend days normally exhibit lower prices than working days and higher for the peak prices than for the off peak prices. The results are conform our expectation and there is more weekend seasonality in the peak hours than in the off peak hours. The speed of mean reversion under normal market conditions, α, indicates how long it will take to return to the mean price level. The results show that α is equal for peak and off peak hours (0.06). The transition probability $Pr\{S_t = 1|S_{t-1} = 1\}$ of staying in the first state is approximately 95% for off peak and peak hours. This implies that the probability of a downward spike is approximately 5%. The transition probability $Pr\{S_t = 2|S_{t-1} = 2\}$ of staying in the second state is higher for off-peak hours. This implies a higher probability of returning to the first state (59.1%) during peak hours. In the first approximation performed through model 1 for the NordPool intraday market prices, we confirm that the behavior of these prices can be captured through a two regimes model. The results for model 1 show that, while prices during state 1 have a low volatility, in state 2 they are characterized by higher volatility and lower levels. Once hydro reservoir levels and wind forecast errors are introduced into the model we are also able to analyze their combined effects on intraday price volatility patterns.

Table 4: Parameter estimates for regime switching model 2

	Off peak		Peak	
μ_1	3.5608*	(0.0217)	3.8637*	(0.0148)
μ_2	-0.2122*	(0.0354)	-0.0800*	(0.0227)
β_1	-0.0166*	(0.0079)	-0.1680*	(0.0071)
α	0.0590*	(0.0039)	0.0585*	(0.0032)
λ_1	3.1137*	(0.0927)	2.6416*	(0.0854)
λ_2	0.1995	(0.1249)	-0.4339*	(0.1274)
κ_1^{hp}	-0.0010*	(0.0004)	0.0005	(0.0004)
κ_2^{hp}	0.0018*	(0.0006)	0.0004	(0.0006)
κ_1^{hn}	0.0023*	(0.0004)	0.0004	(0.0005)
κ_2^{hn}	0.0010	(0.0007)	-0.0003	(0.0006)
κ_1^{lp}	0.0009	(0.0005)	0.0013*	(0.0004)
κ_2^{lp}	-0.0003	(0.0007)	0.0006	(0.0006)
κ_1^{ln}	0.0001	(0.0008)	0.0008	(0.0006)
κ_2^{ln}	0.0020	(0.0012)	0.0017	(0.0017)
σ_1	0.1171*	(0.0014)	0.0841*	(0.0009)
σ_2	0.7090*	(0.0172)	0.4786*	(0.0124)
$p1,1$	0.9575		0.9337	
$p2,2$	0.5508		0.3938	

Notes: Standard errors are in parenthesis. *, denote a test statistic is statistically significant at the 1% level of significance.

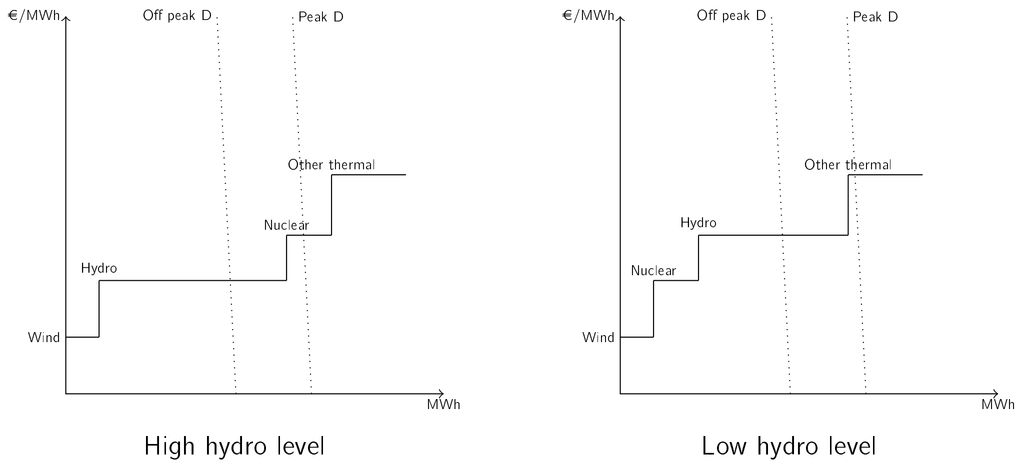
The parameter estimates for the second model with wind dependent transition probabilities are shown in Table 4. High wind production should have a price suppressing effect on power prices, because it gives the hydro power producers the incentive to lower their production and save the water in the basins to use in times of higher power demand. However low wind production will cause an upward effect on the power prices, providing an incentive for hydro power producers to increase production. Forecast errors should have a similar effect. In times of lower forecasted wind power production than realized wind power production this excess of wind power (positive error) should press the intraday power prices down. When the forecasted wind power production is higher than the realized wind power production the deficit (negative error) should have a price increasing effect.

According to Huisman et. al [2013] hydro capacity is valued as a real option that hydro producers have to convert water into power. With a high inventory of water hydropower producers sell at lower prices, because a risk of overflow is present which reduces the potential gains of producers (Torró [2007]). Therefore the value of the real option to delay is almost zero (Huisman et. al [2013]). The opposite is valid during low levels of water inventory. Hydropower producers have the decision to exercise the option to produce power based on the current prices and the expected opportunity loss that arises from using the water later in time against higher prices. This creates high opportunity costs of generating electricity in times of low reservoir levels. These differences in hydropower plant opportunity cost determines the nature of the stabilizing effect of hydro reservoir levels on intraday price volatility under wind forecast errors.

When the actual wind power generation is higher than the forecasted production (positive error) there is an excess of electricity supply planned day-ahead. This excess wind power would imply, to keep the balance between supply and demand, that some powerplants with flexible generation technologies should decrease their production. However, given that during high inventory of water hydropower plants have a low marginal production cost, they could have less willingness to participate in the intraday market to decrease their production which was planned one day prior. From Table 4 we clearly observe that the results for off peak hours with high hydro reservoir levels, which are significantly different from zero, are consistent with the expectations. Firstly according to expectation wind power excess should have a price decreasing effect. The results show that κ_1^{hp} is negative (-0.0010), which means that a positive error leads to a decrease of the probability that the prices will stay in the first state with higher prices. Next to this we observe a positive κ_2^{hp} (0.0018), which leads to an increase of the probability that the prices will stay in the second state with lower prices and also diminishes the probability of switching to the first state with higher prices. We observe that a positive error is being absorbed by hydropower and has a significant impact on the volatility. During high reservoirs levels for the off peak prices wind excess has an increasing effect on the probability of staying in the second state with high volatility but lower prices.

According to the results for the peak hours, when the level in demand is higher, a positive error only shows significance during times of low hydropower capacity. The parameter κ_1^{lp} is positive and significant (0.0013). Meaning that, in times of low inventory of water, a positive deviation increases the probability of staying in the first state with the higher prices. In the descriptive statistics in Table 2 we already observed that the highest prices occur during peak hours and low hydro reservoir levels. During peak hours the demand is at its highest level and in wintertime, when the hydro reservoir levels are lower than average, the demand is even higher because of heating purposes. Therefore lower levels in the hydro reservoir will induce producers to use more expensive sources which eventually will result in higher prices. Figure 2 shows that during peak periods and low level of hydro reservoir fossil fuelled powerplants will be activated. With an excess supply of wind power, conventional power plants should reduce their production, however the high level in demand does not allow the prices to decline, nonetheless it does have a positive impact on the volatility of the prices.

Figure 2: The power supply stack in the NordPool market



Especially for the off peak hours during low hydro reservoir levels the κ's are not significant at the 99-percentage confidence level. This implies that during lower levels of hydro reservoir, hydropower does not play a significant role in capturing the forecast errors in wind power. The price of power is set at the marginal cost of the last unit called when all demand is satisfied. According to Huisman et. al [2013] lower reservoir levels lead to higher marginal cost because of the higher marginal opportunity costs of the option to delay production, therefore a switch in the merit order could occur. The marginal cost of producing 1 MWh with hydro could be higher when the hydro levels are low than producing 1 MWh with for example nuclear. This scenario is represented in Figure 2. In times of lower power demand it is possible that hydropower is not the fuel determining the power price, therefore has no significant effect on the switching probabilities.

A negative error can occur when the actual wind power generation is lower than the forecasted power production. In this case there is a deficit of electricity supply planned day-ahead. This deficit of wind power has to be balanced through trading on the Elbas market to mitigate the balancing cost. In times with a high inventory of water hydropower plants are more willing to cover this deficit on the intraday market. We observe this effect during off peak hours and high water reservoir level. κ_1^{hn} (0.0023) indicates that a wind deficit has an increasing effect on the probability of staying in the first state with higher prices and low volatility. Therefore, under these circumstances this type of error is absorbed naturally by hydropower, hence we would not expect any impact on the volatility since hydro has a stabilizing effect.

5 Conclusion

More intermittent power generation in the supply stack will have an impact on the intraday price volatility adversely for the total balancing costs as part of the overall system cost. The goal of this paper is to analyze to what extent hydropower stabilizes the effect that wind forecast errors can have on the NordPool intraday market prices. We analyse hourly intraday power prices for the Scandinavian market from 2011 until 2013 for peak and off peak hours distinguishing between periods of high and low hydro reservoir levels.

We show that to a certain extent the impact of wind forecast errors on the NordPool intraday prices are stabilized by hydro reservoir levels. The hydropower capacity is a significant price volatility control mechanism mainly during off peak hours, which results from the lower transmission congestion during these hours with lower power demand. This highlights the importance of interconnection in regional electricity markets. With high interconnection prices will better capture the potential positive effects resulting from the interaction between different sources of generation. This is a relevant implication for its consideration in the design of the future European internal market.

During high reservoir levels windpower deficits are absorbed by hydropower but windpower excess is not. This responds to the stronger incentive of the hydropower generators to produce electricity during high reservoir levels, willing to provide flexibility to the power system through its participation in the intraday market which implies increasing their production with respect to the power committed dayahead. Altogether under wind forecast error, the use of hydropower capacity in intraday markets is proven to be an effective volatility control mechanism. This confirmed feature should be take into account when defining future policies targeting the promotion of additional intermittent renewable energy sources.

The integration of wind into the power market needs a more complex market design. An optimal market design should incorporate the market behavior (i.e. the power supply change over the year), which will induce the balancing of the wind power or other intermittent resources with a reduced intraday price risk. Therefore through an overall understanding of the interactions between the level in the hydro reservoirs and wind forecast errors, the expectations of ELBAS intraday prices taken into account, will result in fewer trades closer to real time lowering the balancing costs. These findings provide more insight in how electricity portfolios should be structured with respect to high and low flexibility in the power supply stack.

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