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School of Business

ELECTRICITY PRICE VOLATILITY: ITS EVOLUTION AND DRIVERS

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The Nordic electricity market offers an opportunity to study how intermittently available technologies are shaping up the future of the electricity markets. This work presents an empirical research on how the wind-produced energy affects the market and what challenges does wind power brings into it. The main proposition is that the wind power output makes the electricity prices less predictable and increases the allocative inefficiencies that already exist in the electricity market. In particular, the study is aimed at estimating the effect of wind power generation on the electricity price volatility in the Nordic electricity market. Additionally, the gap between the mean system price and the mean bidding area prices is described and analysed. Since most standard financial contracts traded in the Nordic countries use the system price as reference price, there is a need to investigate what factors affect the gap between the fictitious clearing price for the whole Nordic region and the actual electricity price at the moment of energy purchase. For conducting the empirical part of the analysis, the linear regression equations are constructed and used. The main objective of this thesis is to capture the wind power effect after controlling for seasonality, trend and exogenous supply shifters. This work also provides a starting point for discussions about the possibility of a new metering technology introduction (such as Smart Grid technology) to the Nordic electricity market.

Keywords: Nordic electricity market, electricity price volatility, system price, Nord Pool, wind energy

Contents

1 Introduction

1.1 How does the wind power affect electricity markets?

Around the world, renewable energy capacity is on the rise. According to the Renewable Energy Policy Network for the 21st Century (REN21) report, renewables contributed 19.2% to the global energy consumption in 2014 and 23.7% to the global electricity generation in 2015 [1]. The drastic increase in the intermittently-available energy generating technologies is mainly due to falling costs [2], policies favouring renewable energy, and concerns over greenhouse gas emissions from fossil fuel industries.

Throughout the last 20 years, the influence of renewable energy sources, apart from hydroelectric capacity, has remarkably increased in the Nordic countries as well. The energy system in Sweden, for instance, is now characterised by very low use of fossil fuels and a high share of renewables in all sectors apart from transport. According to the European Commission Report [3], the share of renewable energy in final energy consumption in Sweden is among the highest in the EU (at about 54%) and already exceeds the 2020 target of 49%.

In recent years, wind power has been the fastest-growing source of renewable energy thoughtout the world, and the Nordic countries are experiencing the increase in the wind power output, too. Since 2000, Swedish wind-energy production has increased from 0.45 to 16.6 TWh/year (Table A.2). And this growth is accelerating: wind power production has more than tripled since 2010. Today, there are around 3,100 wind turbines in Sweden [4].

In other Nordic countries, such as Finland and Denmark, wind power has also been on the rise. By the end of 2015, Denmark had the world's biggest share of total wind power capacity *per capita* [1]. In Finland, wind power production was about 2.3 TWh (2.8% of the Finnish electricity consumption) in 2015 [5].

Amongst all other intermittently-available energy resources, wind power is the first one to reach significant capacity introduction worldwide. Its significant share in the power generation mix and its unpredictable nature increases the complexity of electricity markets' operations [6]. While the amount of wind-generated energy is growing, this opens up the discussion on how the high levels of wind power capacity penetration affect the electricity markets. There are different channels through which the wind power introduction impacts the markets:

1. Wind energy integration costs: wind power enters electricity market with certain costs of scheduling and operational adjustments [7]. This is inevitable since the intermittent nature of wind power generation creates highly unpredictable deviations in the supply. This, in turn, requires changes in other energy generators' operations to prevent imbalances between the supply and demand. As currently electricity is not storable, supply and demand have to be matched immediately to avoid temporary disequilibrium [8]. Accordingly, the supply from the other energy generators should be decreased when there is an abundance of the wind-produced energy in the power system, and it should be increased when there is a lack of wind. If the equilibrium between the supply and demand cannot be achieved in time, this can lead to extreme electricity prices. Hereby, the costs for introducting the wind energy generators to the power system are unpreventable. For instance, according to the report by the European Wind Energy Association [9], the costs of wind power integration into the Danish electricity market with the 20% of wind power penetration was, on average, about 0.3 - 0.4c€/kWh of wind power generated.

2. Social costs and benefits of renewable energy: there is no particular consensus on how to assess the benefits arising from the wind capacity introduction. For instance, in the paper by S.Kennedy [10], social benefits are based upon the avoided energy, capital, and environmental costs due to the replacement of conventional power sources with wind-produced electricity. The author concludes that the social benefits from the wind power energy are negative and they decrease with the increasing penetration of the wind power. It should be mentioned that this result is very sensitive to the choice of the conventional generation technologies: if high environmental costs had been considered, the

social benefits would have been positive.

In the recent paper by S.Fogelberg and E.Lazarczyk [11], the authors study the costs and benefits of the renewables in the Danish electricity market. The authors consider whether the necessity of the frequent start-ups and shut-downs of traditional energy generating stations (coal, gas, oil, hydro) due to volatile wind generation could potentially increase the failures or needs for maintenance. The authors conclude that there is no significant adverse effect on other generators' failure rates due to systematically volatile wind power output in the short run.

3. Spot electricity market price level and its variance: in the paper by C.Woo et al.[12], the analysis of the Texas' electricity prices concludes that there is a statistically significant decline in spot price level in response to the increased wind power generation. Meanwhile, the variance of electricity spot prices tends to increase when the more wind capacity is added. In the paper by N.Cutler et al.[6], the analysis of the Australian spot electricity prices shows that the price level is decreasing in response to the higher wind power output as well, although no analysis of the price volatility is conducted. The recent study of the German electricity market by J.Ketterer [8] also concludes that additional wind power output reduces the price level but increases its volatility.

This work is a contribution to the existing literature on how the escalated penetration of the wind power capacity affects the electricity spot price variance. Alhough such studies were conducted for some geographical regions (Germany, Australia, the US), the empirical studies for the Nordic region are scarce. The question about the spot price variance in the Nordic electricity market has been recently raised in the paper by M.Liski and I.Vehviläinen [13]: no significant relationship between the wind power output and the price volatility was found. This finding is not in the line with the previous empirical studies and one reason for this may be that the authors used the fictitious clearing price for the whole Nordic region, and not the actual country-specific market clearing prices (which are the actual price of electricity purchase).

Intuitively, there is a solid explanation to the question about why electricity prices become more volatile when the renewable energy capacity increases. It is known that controlling the energy output from intermittent energy generators is harder than doing this for conventional energy sources. If there are difficulties in meeting the market demand in time, electricity grid operators may have to purchase extra energy to supply the market and to avoid shortages. In such a scenario, equilibrium market price will be higher compared to the price when a grid operator provides necessary supply in time without purchasing it from somewhere else. With an increasing share of the intermittently available energy resources, this should be happening more frequently since the electricity supply is becoming less predictable.

In the thesis, I am investigating whether the increased share of energy produced by renewables leads to the above described inefficiencies in the Nordic electricity market. In particular, I am studying whether prices have become more volatile in response to the more unpredictable nature of the energy supply. If there is a positive correlation between electricity price volatility and wind-generated energy output, this brings up the discussion about whether the electricity demand can be made responsive enough to follow the volatile electricity prices and whether this can be achieved with a new metering technologies introduction. Additionally, I am studying the factors that make the country-specific clearing prices to deviate from the equilibrium price for the Nordic region.

1.2 What can enhance the price elasticity of electricity demand?

Electricity prices have been extensively studied since the era of deregulated electricity markets began, as well as there was a sharp increase in interest towards consumer behaviour in the electricity market. There is a plethora of studies and field experiments that explore the degree of consumers responsiveness to the changes in the electricity prices. One reason to study this is to find a way to decrease allocative inefficiencies that arise in the electricity market since virtually all retail consumers of electricity are charged the price that does not reflect the wholesale price at the moment of consumption [14]. There is a consensus among economists that a shift in the pricing paradigm towards time-varying rates whould significantly decrease these inefficiencies and, as a result, would raise welfare [15].

The most efficient pricing paradigm would be a form of dynamic prising: a real-time pricing (RTP). Theoretically, the movement from the standard flat rate tariff to the RTP should not only remove the allocative inefficiencies, but also provide the static allocative efficiency improvements. When the RTP is in use, the consumers pay the real-time electricity price at the moment of consumption and there are gains from an electricity consumption shift from the peak-hours when the marginal cost of production is high to the off-peak hours when marginal cost is low. Furthermore, in countries with deregulated market structure, moving customers to the time-varying prices can reduce firms' ability to exercise market power which they do by imposing a high mark up over the marginal price in the hours of inelastic demand [16]

However, another question arises: will consumers be responsive to the changes in electricity price? That is, will they shift their consumption from the peak, high-demand hours to the off-peak, low-demand hours?

In the paper by F.Ahmad and S.Sanem [15] and in the paper by J.Caroll et al.[17], the authors conclude that electricity demand can be responsive to price changes if consumers are provided with necessary information about the current electricity prices. Installing Smart Grid technologies (home-installed indicators that notify users whether the price of electricity is high or low with a user-friendly colouring code) provides households with necessary information on the current price at the moment of consumption and thus may potentially increase the degree of consumers price elasticity.

Admittedly, the costs for the metering infrastructure introduction are considerable and the main challenge is to make them as low as possible. According to the article by A.Faruqui and S.Sergici [15], a good portion of the investment could be covered by reductions in the power generation costs that is brought through the demand response. The higher the magnitude of the demand response is, the better the chances are that the costs of an alternative metering design installation will be covered by it.

An extra argument in favour of a new metering technologies introduction is a connection between the increasing renewables capacity and electricity prices. One way of examining a possible relationship between electricity prices and intermittently-available technologies is to investigate whether there is a positive correlation between the electricity price volatility and the capacity of renewables. This approach may reveal whether the electricity prices become less predictable (more volatile) when the share of energy from the renewable resources is increasing. If the prices tend to be more volatile in response to the increasing renewables capacity, this will have a negative effect on the welfare since the allocative inefficiencies are rising even further in such a scenario.

Thus, finding the evidence in favour of a positive correlation between the electricity price volatility and the renewables output brings extra incentives for a policymaker to reconsider the current electricity market design. In this thesis, I am investigating this question for the Nordic electricity market. Since the wind power is the biggest renewable source in the region, my research is aimed at examining a possible relationship between the electricity price volatility and the wind-power output.

This thesis is organized as follows. In Section 2, the relevant literature on the interaction between the wind power generation and electricity prices in the markets with a high degree of wind power penetration is summarized. Additionally, I will focus on studies that investigate the price volatility behaviour. In Section 3, the descriptive statistics for the intra-day monthly price volatility in the Nordic electricity market is presented. Moreover, it is discussed how the intra-day price volatility has changed in the last sixteen years. Additionally, the monthly volatility measure and the data used for the calculations are presented and explained. Section 4 presents the model and the summary of the regression results and Section 5 provides an analysis on the gap between the system and the bidding area prices. Section 6 provides conclusive remarks and discussion for future research. Details on descriptive statistics and some of regression estimations are provided in the Appendix.

2 Literature overview

Various studies evaluate how the increased wind energy generation affects the wholesale electricity price by focusing on the cost savings arising from wind generation [8, 12, 18, 19, 20]. This effect is studied either by analysing the historical electricity prices data or by using the simulated electricity prices. The studies that wind power tends to have a negative effect on the wholesale electricity prices, although the magnitude of the effect varies. The magnitude depends on what electricity market is under investigation as each has a different energy generator mix.

Empirical studies of electricity prices and their volatility have been conducted in the US, Canada, some European countries, Australia and New Zealand. In the US, a lot of studies are focusing on the Texas electricity market as it has the biggest share of installed wind capacity amongst all other states and it is the largest electricity-consuming state in the nation. In the paper by E.Nicholson et al. [18], the negative relationship between electricity prices in the Texas electricity market and wind generation was found. Notably, the marginal effect is greater during the day, meaning that electricity supply during the day-time is less elastic (the slope of the supply curve is steeper). The same conclusion is derived in the paper by C.Woo et al. [12]: increases in wind generation tend to reduce the level of electricity spot prices. The paper has one more valuable insight: increases in wind power output tend to enhance the daily spot-price variance. The magnitude of the increases in price volatility varies across different electricity markets: from less than 1% to 5% in response to a 10% increase in the installed capacity of wind generation.

When reviewing empirical studies in Europe, one cannot overlook the German electricity market. The growth of renewables-generated energy started since 1991 [21]. By the end of 2014, Germany was the largest producer of renewable energy within the EU-28, with an 18.4% share of the total energy produced [22].

There is a recent paper by J.Ketterer [8] that studies the relationship between intermittently available wind power and German electricity market prices. The findings corresponds to the previously stated empirical results: as the supply curve becomes flatter, the wind-induced price decrease is less profound. Additionally, the author uses a generalized autoregressive conditional heteroskedasticity (GARCH) model to test whether changes in wind power output have an effect on price volatility. The approach is not new[1], but very appropriate since a GARCH model can replicate the volatility behaviour properly. Moreover, Engle's (1982) test for autoregressive conditional heteroscedasticity (ARCH) in the residuals confirms that ARCH effects are present. One more interesting finding is recorded: the day-ahead price is negatively correlated with the high wind forecast. Thus, the market adequately anticipates that high volumes of wind-generated power dampen electricity prices as the energy supply is forecasted to be in abundance. This finding is in line with previous studies by T.Jónsson et.al [26] and C.Woo et al. [12].

Another paper that studies the German electricity market is written by F.Sensfub et al. [20], and the authors use the simulated hourly spot market prices. One caveat of this approach is the understated levels of price volatility: the simulation does not provide high spikes in the hourly price data. Regardless this price volatility simplification, results indicate price reductions when the amount of wind-generated energy grows. As the data derived from simulation, the conducted sensitivity analysis with different scenarios concludes that the effect is persistent.

The Irish electricity market represents an interesting case study as the island's limited interconnections allow to estimate wind-generated effect on electricity prices more clearly. One paper by V.Cosmo and L.Valeri [19] finds a negative and significant effect of the wind power on the electricity price level although the wind capacity penetration is very modest (by the end of 2011, 2000MWh). Another paper by A.O'Mahoney and E.Denny [27] finds out the same results for the Irish electricity market, although the authors use one year of the historical prices data only. The most recent paper by E.Denny et al. [28] is assessing the wind impact by using two different approaches: a conventional linear regression model and a more engineering-specific approach that mimics the energy pricing formation. Both models justifies significant

[1] Previously, GARCH modelling was used to examine the relationship between trading volume and price volatility [23, 24] or to explore how changes in market design affect the volatility of price [25]

costs savings arising from wind power generation, as penetration of wind energy reduces wholesale electricity prices.

While the dampening effect of wind generation on electricity prices level is well-studied in many papers, the literature on how wind power generation affects electricity price volatility is scarce and inconclusive. Not only the number of studies is insufficient to make appropriate conclusion, neither there is a similar approach on what price volatility measure to use (daily, weekly, monthly). In the paper by R.Green et al. [29], the British electricity market is studied. The study considers daily variation in electricity prices and it is able to make insightful inference about price behaviour during the day: the variation in prices is greatest in the peak demand hours, because a given variation in wind output produces a greater variation in prices when they are already high. However, no conclusions can be made about the impact of increased wind power generation on price volatility in the long-run, as such a relationship is not studied in the paper. Additionally, the paper finds out that the effect is more persistent during summer months. This particular finding is also recorded in the study of the Australian electricity marlet by H.Higgs et al. [30]: throughout September, November, December and January (summer in Australia), the price volatility is higher than it is in the rest of the year.

The US's electricity market (New England) was studied in the recent paper by C.Brancucci at al. [31]. The authors examine not only the impact of wind power on the mean hourly electricity price for the different levels of wind penetrations, but also how wind power affects hourly price variance. In line with the previous research of the US electricity market [12], the authors find out that wind power increases hour-to-hour electricity price volatility as wind penetration increases.

Electricity price volatility behaviour has been recently studied for the German and the Danish elecrticity markets by T.Rintamäki et al.[32] and the findings are different when the daily or weekly electricity price volatility is considered. Weekly volatility is increasing in both electricity markets when intermittently available generators are introduced. Daily volatility, on contrary, behaves differently: in Denmark, it is decreasing and in Germany it is increasing when the wind power output is growing.

One way to explain the inconsistency in the results for the daily volatility is to remember that German and Danish electricity markets have different renewables generation mix: while Denmark has only wind power, Germany has both wind ans solar energy. As solar power is produced only during peak hours, this decreases daily price volatility by decreasing high peak hour prices. As wind and solar power have opposite effects on volatility, the results for German electricity daily volatility is inconclusive.

In order to understand whether there is a need of changing the current electricity market design, it is necessary to conduct a relevant empirical study of the electricity market and the electricity prices development. As the existing literature does not provide enough insight on how the price volatility changes through time, there is a need to study the question.

3 Descriptive statistics of the price volatility in the Nordic electricity market

3.1 The Nordic market

The Nordic market is a day-ahead and intra-day market for wholesale power across nine European countries. In this study we focus on four of them: Finland, Sweden, Norway and Denmark. The Nord Pool Spot (NPS) market was established when Norwegian parliament decided to start the electricity market deregulation in 1991. Since then, other neighboring countries jointed in and now there are several price zones for each of the country.

The NPS is a platform at which the supply and demand bids are made. The bids result in regional hourly equilibrium price, or the system price. System price is an unconstrained market clearing reference price which is calculated without any congestion restrictions by setting capacities to infinity [33]. As long as generating capacity is sufficient, the system price is equal to the wholesale electricity price for all four countries.

The Nordic spot market closes at noon every day when the bids for supply and demand are balanced and commitments for energy delivery and consumption are made the following day on an hourly basis. There is a time interval of at least 12 hours between the moment of transactions and the time when the actual trades take place; this leads to unavoidable fluctuations in the actual supply and demand [34].

Due to those fluctuations, some trades are not feasible at the moment of trade. Whenever the lack of transmission capacity prevents cross-border trade, the "area prices" differ from the system price [35]. Each region has at least one bidding area: Finland has one whereas Norway has five of them. All bidding areas are presented in Fig. 1 (the map is obtained from the official Nord-Pool website [33]).

Figure 1: The Nordic market and bidding areas overview [33]

The amount of energy produced by different resources varies by region. The descriptive statistics of how much power output (TWh) is generated by each Nordic country is presented in Table A.1 of Appendix: each country has its own generation mix and this allows to investigate how the electricity prices change when the wind-generated power is increasing depending on the capacity of other energy resources (hydro, thermal, nuclear or combined heat and power (CHP)). Based on the descriptive statistics found in Table A.2 of Appendix: it can be clearly seen how rapidly the renewable energy generators are entering the Nordic electricity market.

This study is aimed at detecting whether there is a persistent change in price volatility for each bidding area when the change in wind generation happens. Previous study by M.Liski and I.Vehviläinen [13] explored whether there is such a relationship between the *system price* and wind output. Here the set up is different: the main focus is at the real market price that cleared the market. In the paper by M.Liski and I.Vehvilainen no significant effect was found, but at this study the results are different.

3.2 Intra-day price volatility

The first step of the study is aimed at exploring the evolution of price volatility for the period 2000-2016. One possible way of looking into this development is to examine whether the intra-day volatility has increased. A simple approach that reveals a change in the intra-day price volatility is to look at the historical differences between the peak and off-peak electricity prices.

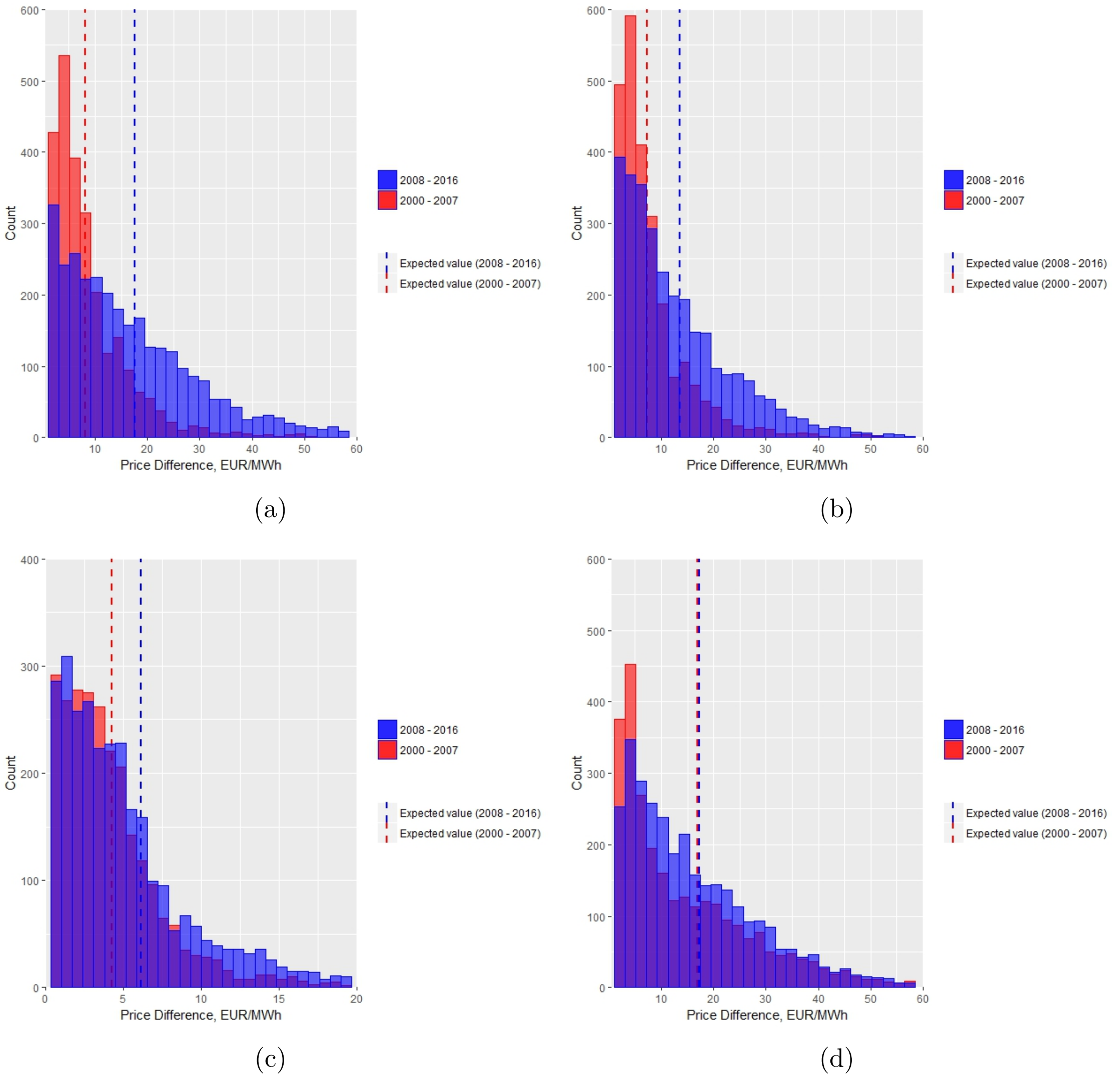
As it was stated before, electricity prices vary significantly throughout a day and there are the so-called peak and off-peak hours: the expensive peak-period hours are characterised by inelastic electricity demand and during the inexpensive off-peak period hours, the demand is low. Based on the dataset containing the hourly electricity prices for Finland, Sweden, Norway and Denmark (obtained from the Nord Pool FTP server [33]) we can calculate the differences between the peak and off-peak prices for the period from 2000 to 2016 [2].

The best way to present the results is to construct the histograms and to calculate the expected values for the price differences in each bidding area. In order to see whether the price differences are increasing through time, let us divide the time

[2]The off-peak hour is the same for all countries (3 a.m.); the peak hour in Finland, Norway and Sweden is 8 a.m., whereas the peak hour in Denmark is 11 a.m.

period into 2 equal sub-periods: from 2000 to 2007 and from 2008 to 2016.

The distributions of the price differences for each Nordic country are presented in Fig. 2. [3]



(a) (b) (c) (d)

Figure 2: Price differences between the peak and off-peak hours (EUR/MWh). (a) For Finland (FI). (b) For Sweden (SE+SE4). (c) For Norway (NO1). (d) For Denmark (DK1).

As it can be seen from the histograms, the peak hours are always more expensive than the off-peak ones. Additionally, one can notice that the differences vary

[3] In 2011, Sweden has been split into 4 different bidding areas: SE1, SE2, SE3 and SE4. The histograms are composed by merging the data for the whole Sweden till 2011 and the data for the appropriate bidding zone after the split.

significantly from region to region. The expected price differences for the 2 sub-periods for each country can be found in the table below (Table 1):

Table 1: Expected price difference for each Nordic country

Bidding area	Expected price difference (EUR/MWh)	
	From 2000 to 2007	From 2008 to 2016
FI (Finland)	8.18	17.55
SE+SE4 (Sweden)	7.3	13.63
NO1 (Norway)	4.23	6.17
DK1 (Denmark)	17.01	17.2

Based on the descriptive statistics presented in Table 1, one can conclude that the intra-day price volatility has risen significantly in Finland and Sweden whereas in Norway it has experienced a modest increase; for Denmark it remains at the same level. These findings indicate that the electricity price has become more volatile during a day and this alone should have enhanced allocative inefficiencies in the electricity market since consumers cannot efficiently adjust their demand to the rising price variance under the fixed electricity contracts. Additionally, this indicates the necessity of a more sophisticated analysis that can help finding the reasons of the increasing price volatility.

The next step is to explore the price volatility evolution by looking at the monthly price volatility measure. This involves constructing the appropriate measure and exploring its development through the period 2000-2016.

3.3 Volatility measure and graphical examples

To study the causes of the increasing price volatility, it is necessary to derive a volatility measure that describes the degree of variation of a price series over time. The data for calculating price volatility is obtained from the Nord Pool website [33] and covers the period from 2000 to 2016. It is the hourly electricity spot price data that reflects the actual price of energy purchase at every hour. This price is different from the system price (regional hourly equilibrium price) if not all trades are feasible.

In order to estimate monthly price volatility, the standard volatility measure (σ^2)

is used:

$$\sigma^2 = \frac{1}{n-2}\sum_{i=2}^{n}(r_i - \bar{r})^2, \tag{1}$$

$r_i = \frac{p_i}{p_{i-1}}$

$\bar{r}$ is the mean of returns of the month,

p_i is spot price for the hour i,

n is the number of hours in a month.

The monthly electricity price volatility measure depicts the degree of price variation within a month. Additionally, the measure captures the seasonal variation in price volatility which is essential for the analysis since energy output from hydro and wind resources is also very seasonal (see Fig. 3)[4].

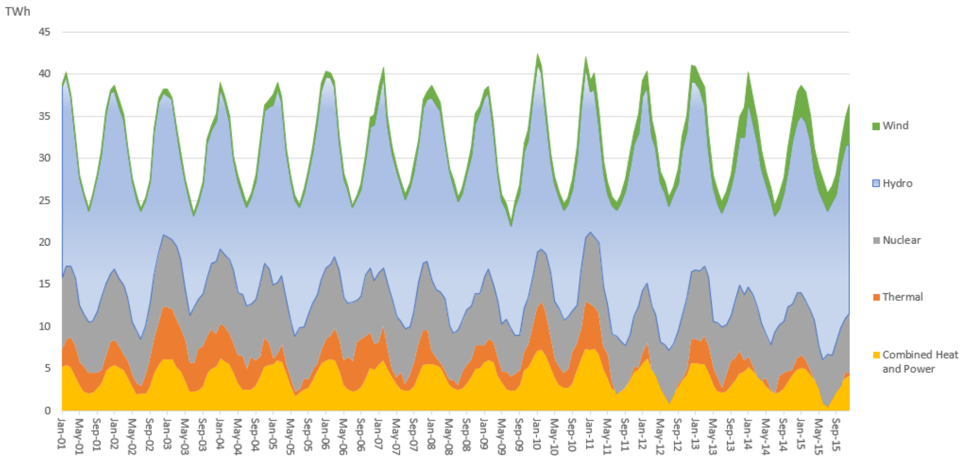


Figure 3: Monthly Nordic energy production per type

Determining whether there are intra-day changes in price volatility in response to different levels of wind (in the same way as it has been done for Danish, German and British electricity markets [8, 29, 32] is out of scope of this study.

3.3.1 Finland

After computing the volatility estimates for each bidding area, let us review the price volatility evolution in all Nordic countries, starting from Finland (Fig. 4). The time period under consideration is 2000-2016.

[4]The data for constructing the graph is obtained from the paper by M.Liski and I.Vehviläinen [13]

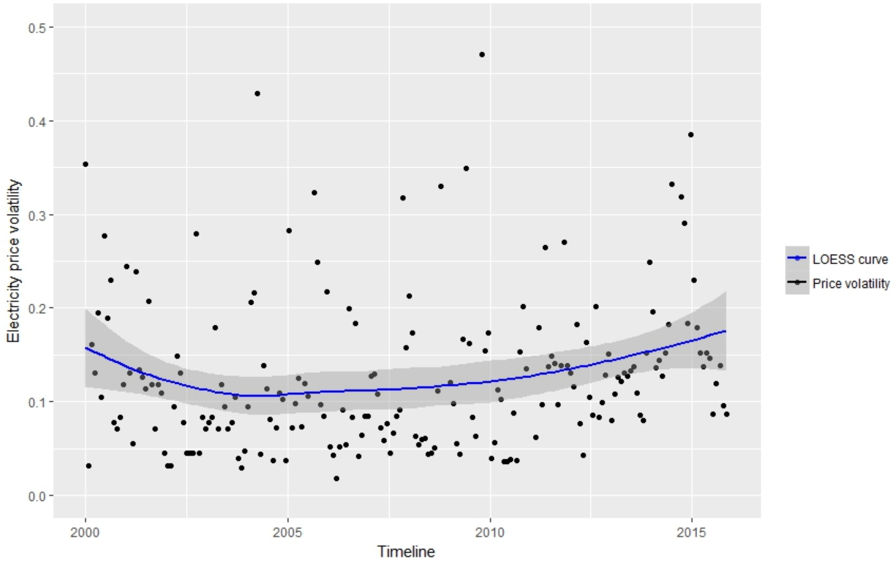


Figure 4: Electricity price volatility in Finland. Locally weighted scatter-plot smoother (LOESS) line is added to the graph to capture the development of price volatility

In order to enhance the visual information in Fig. 4, non-parametric local regression method (loess smoothing) was used. Local fitting of polynomials has been used for many decades to smooth time series plots in which the x_i are equally spaced [36].[5]

Local polynomial regression line depicts that there is a quadratic trend in price volatility for the bidding area. At first, we observe a downward sloping behaviour of price volatility. One explanation for this are the extremely dry hydrological conditions in the fall-winter season of 2002-2003. As Nordic energy sector is relying on hydro resources, this caused the spot prices to spike and to a massive media attention about it. According to E.Amundsen and L.Bergman [35], this led to a reduction of electricity consumption and to a change in household electricity contracts: away from the variable contracts (ones that give the highest retail prices and volatility during the period) to either spot based- or fixed price contracts. Notable, there is a clear upward sloping behaviour in price volatility in Finland from 2004 onwards.

The next task is to check whether the trend in price volatility can be explained by the amount of wind-generated energy. A graphical examination of the proposed claim is presented in Fig. 5.

[5]In the statistical software package R, the "loess" function performs necessary computations and plots the smoothing line with the 95 % confidence interval.

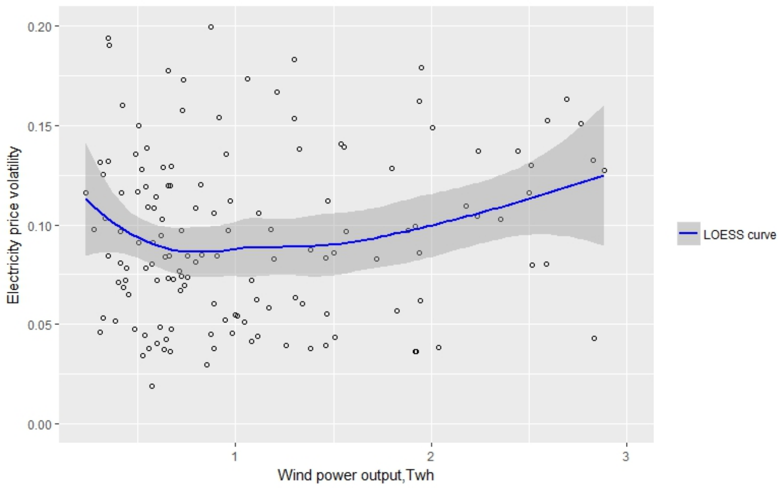


Figure 5: Price volatility against wind output in Finland (TWh/month)

This graph combines monthly price volatility in Finland and the level of wind-generated energy (in TWh per month) in the whole Nordic region. Thus, the scatter plot in Fig. 5 helps examining whether the months with higher price volatility are also the ones when the higher wind-power generation takes place.

The graphical analysis does not explicitly reveal the direction of possible relation between the wind generation and the price volatility in Finland. In the next section, a more systematic approach for determining the causes for the rising price volatility is presented.

3.3.2 Sweden

As it can be seen from Fig. 1, Sweden is now divided into four bidding areas: Lulea (SE1), Sundsvall (SE2), Stockholm (SE3) and Malmö (SE4). The decision to make this split was done by a local transmission system operator on November 2011. The aim was to relieve grid congestion and improve its utilisation from north to south. The majority of Swedish population lives in the south and consumption is far greater there (SE3, SE4), whereas the most of the country's power generation infrastructure is based in the north (SE1 and SE2). While the price volatility in the SE1-SE3 areas are following the same trend and these areas often have equal electricity prices, the SE4 area is influenced by the German electricity market prices and has the greatest fluctuations and the highest prices.

Fig. 6 is capturing the effect of the split on the price volatility development in the Swedish electricity market. Till 2011, the volatility for the whole Sweden is plotted and starting from November 2011, the volatility in the newly introduced bidding areas is depicted.

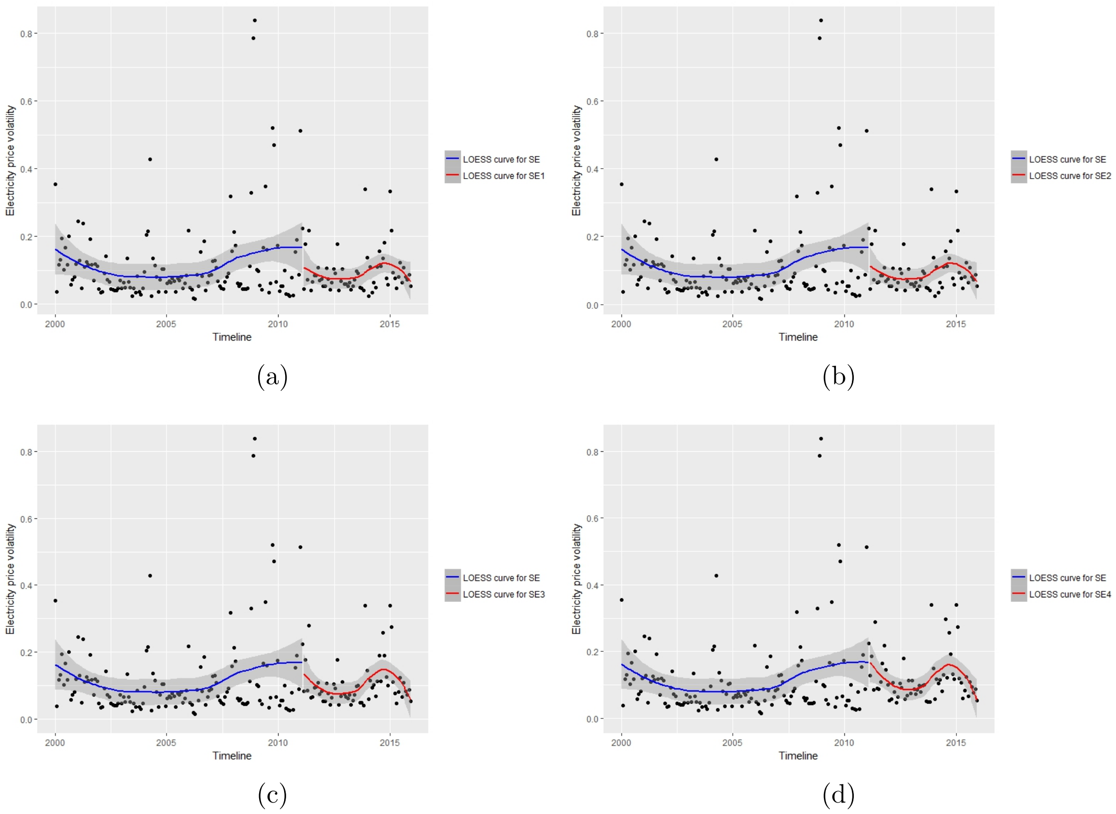
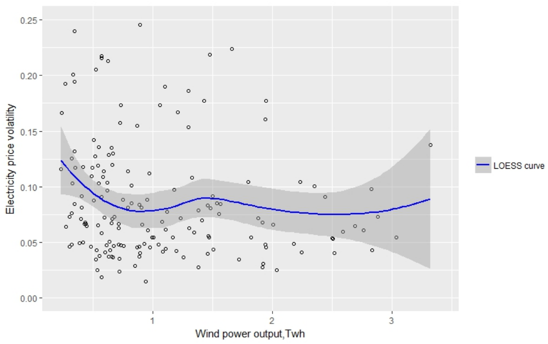


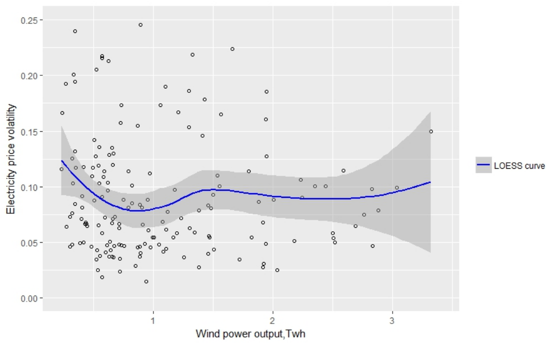
Figure 6: Electricity price volatility in Sweden. (a) Volatility in SE-SE1 areas. (b) Volatility in SE-SE2 areas. (c) Volatility in SE-SE3 areas. (d) Volatility in SE-SE4 areas.

The graphical analysis depicts a steady increase in the price volatility until 2011 (except for the period from 2002-2003 when there was a lack in the hydro-resources) and then the split of the SE bidding area affected the newly added price zones differently. The split led to a drop in price volatility for the SE1-SE3 bidding areas, but it was not the case for the SE4 area. For a more precise analysis of how the structural change affected the Swedish electricity market one may apply the Regression Discontinuity Design (RDD) using a 2011 year as a cut off. As there is the same pattern for the SE1-SE3 bidding areas, I review only one of them in my analysis, the SE1 zone. The price volatility in Malmö (the SE4 price zone) depicts a different behaviour and I shall examine this area in details as well.

The scatter plot presented in Fig. 7 combines the price volatility and the levels of wind power output for the period from 2001 to 2015: it explores whether the months with higher price volatility are also the ones when the higher wind-power generation occurs.



(a)



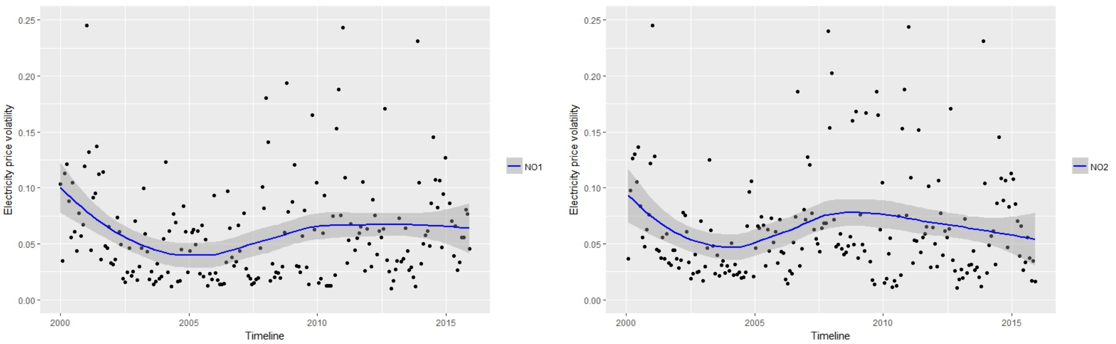
(b)

Figure 7: Price volatility against wind output in Sweden (TWh/month). (a) SE-SE1 areas. (b) SE-SE4 areas.

Graphical analysis is ambiguous as no clear trend can be seen from it. The 95 % confidence interval is widening when the wind power output increases. Although the LOESS curve is slightly positively inclined, no conclusion about the relationship between the wind and the price volatility can be drawn from here.

3.3.3 Norway

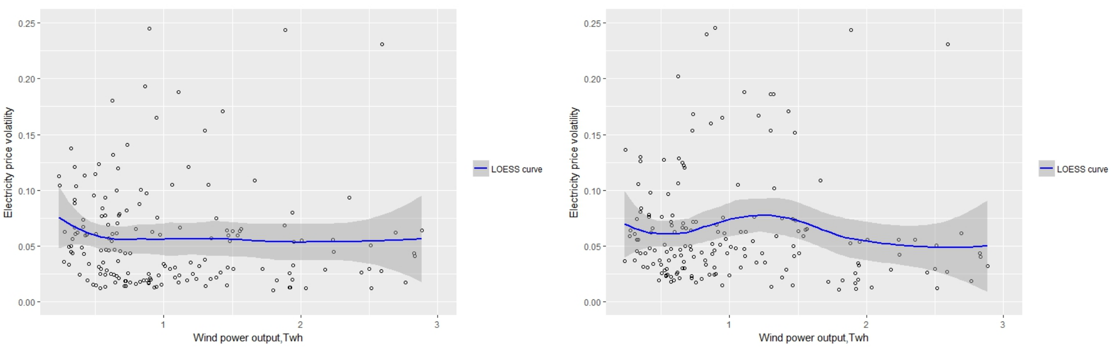
The number of Norwegian bidding areas vary: today there are five of them. Oslo (NO1) and Kristiansand (NO2) are being used since 2000 and Tromsø (NO4) and Bergen (NO5) were added in 2010 due to either long-term congestions in the regional and central grid system or a lack of energy in certain geographical areas (The western area (NO5) was established due to the low reservoir content in western Norway and possible lack of energy)[33]. The main focus of the paper will be on those Norway bidding areas that have more historical data (NO1 and NO2, although the NO1 area is the most consistent one as it has experienced the fewest number of mergers and adjustments).



(a) (b)

Figure 8: Electricity price volatility in Norway. (a) Volatility in NO1 area. (b) Volatility in NO2 area.

Fig. 8a depicts a slight increase in the price volatility that starts from 2010. This increase might have been triggered by the structural change in the Norwegian bidding areas, but it is worth studying the relation between the wind power output and the price volatility as well. Fig. 8b displays no distinguishable trend for the price volatility.



(a) (b)

Figure 9: Price volatility against wind output in Norway (TWh/month) (a) NO1 area. (b) NO2 area.

The graphical analysis presented in Fig. 9a does not reveal the existence of any significant relationship between the price volatility and the wind energy in the NO1 area, although there is some interconnection between these two variables for the NO2 area (Fig. 9b). In order to investigate what is causing the increase in the Norwegian price volatility, additional covariates are ought to be introduced and analysed. The more detailed discussion is presented in the Section 4.

3.3.4 Denmark

The historical trend of the Danish price volatility is of a particular interest to a researcher as this country has the biggest share of the wind-produced power in its generation mix among other countries in the study. More than that, by the end of 2015 Denmark had the world's biggest share of total wind power capacity *per capita* [1].

Historically, Denmark is split into two bidding areas: Western Denmark (DK1) and Eastern Denmark (DK2) (see Fig 1). The magnitude of the price volatility for Denmark is historically higher than that for the rest of the countries in the analysis (see Fig. 10). As Denmark is located between the Nordic hydro-based generating system and the thermal-based continental oriented production, the Danish wholesale spot prices are usually higher than the system price of Nordic countries and lower than the continental prices.

Most of the time, the prices in the DK1 area are lower than the prices in the DK2 zone since it has a higher wind production output and a high import of the hydro electricity from Norway. There is an increasing number of outliers for both the DK1 and DK2 areas (with price volatility in the DK1 zone being more unstable than that in the DK2 area). On way to explain this high price variability is via its connection to the wind power output.

In order to see if there is a relationship between the wind output and the price volatility for both Denmark's areas, one need to construct a scatter plot for the data. After considering the graphs presented in Fig. 11, it is clear that the periods with the high price volatility tend to coincide with the periods with the high wind power output.

Previous analysis of the electricity price evolution revealed that there is a lot of spikes in the price volatility in the DK1 area and these spikes seem to happen

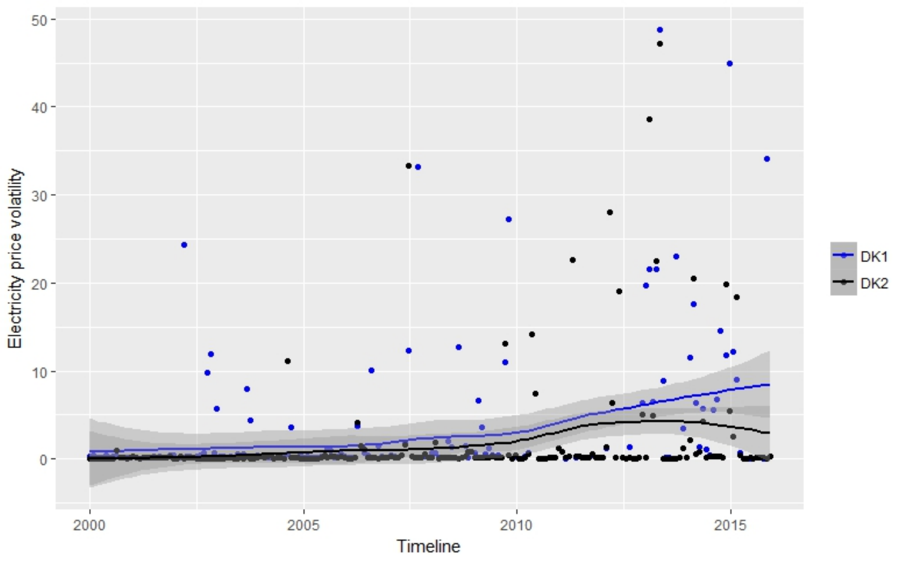
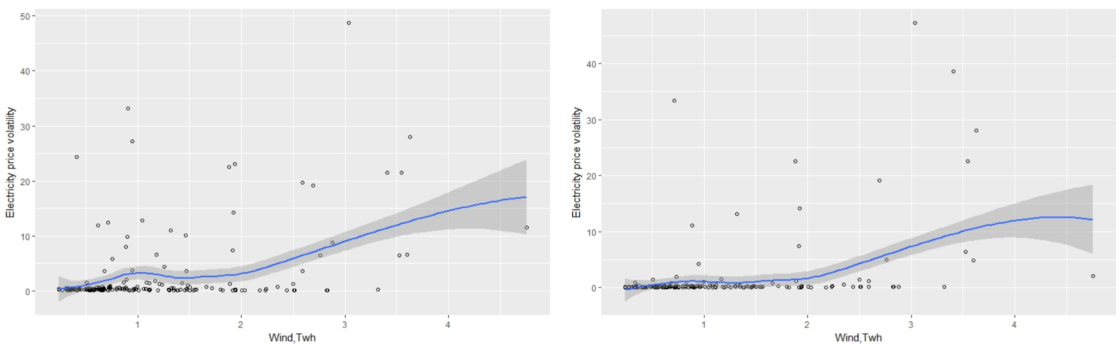


Figure 10: Electricity price volatility for DK1 and DK2 area



(a) (b)

Figure 11: Price volatility against wind output for Denmark (TWh/month) (a) DK1 area. (b) DK2 area.

when the higher levels of wind energy are generated. The same conclusion can be drawn based on the Fig. 11b, although the effect is less pronounce. The next section presents the empirical strategy for estimating the wind effect on the price volatility.

4 Empirical strategy: estimates for the price volatility

As was stated earlier, the volatilty measure is calculated using the hourly electricity price data from 2000 to 2016 obtained from the Nord Pool website [33]. The rest of the data is obtained from the paper by M.Liski and I.Vehviläinen [13]. The data covers the period from 2001 to 2015. The data is aggregated to the monthly level: this allows to explain seasonal variation in the price volatility by observing seasonal variation in the covariates. Additionally, monthly dummies are added to the regression to control for fixed seasonal effects. Exogenous covariates that are used for capturing the relationship between price volatility and wind output are the following:

- WIND (W) covariate depicts the average for the wind production over a month for all countries in the Nordic region;
- INFLOW (I) covariate is the inflow of water resources in a region. It is expressed as deviation from its mean seasonal value: this allows to control for the effect that changes in the resource availability have on the price volatility;
- RESERVOIR (R) covariate represents the power output from hydropower resources. It is presented separately for each country, but in practice the outcome is determined by the Norwegian and Swedish reservoirs, as Danish hydro resources are very scarce and the optimization of Finnish hydropower is very limited [13]. It is expressed as deviation from the mean seasonal value;
- HDD covariate is the temperature measured in Nordic heating degree days. Temperature affects the demand for electricity mainly through electric heating.

Equation 2 shows the proposed breakdown for the electricity price volatility. The empirical strategy is to estimate how sensitive the price volatility is to the changes in the wind power output using the exogenous supply shifters. To simplify the interpretation of the results, the natural logarithm of the volatility measure is taken.

$$\ln(\sigma) = \sum_{i=1}^{12} a_i D_{it} + \gamma_t + \beta_1 W + \beta_2 I + \beta_3 R + \beta_4 HDD + \epsilon_t, \tag{2}$$

where

σ is price volatility,

D_{it} is a set of dummy variables for each month,

γ_t is a linear trend component.

4.1 Finland

The regression results for the price volatility in Finland are presented in Table 2 below. Each column of the table represents the estimates obtained in a particular regression: the first regression includes only the seasonal dummies whereas the fifth regression includes all the covariates specified in Equation 2.[6]

Based on the table output, it is evident that the wind covariate has a statistically significant positive correlation with the electricity price volatility. In the second regression (column 2) that includes the main effect and the seasonal dummies, the estimated effect of wind on price volatility is 0.26. This coefficient can be interpreted as a 26% increase in the Finnish electricity price volatility in response to a 1 TWh/month increase in the wind-power output in the Nordic region.

Even after controlling for the trend and the possible exogenous supply shifters (the amount of hydro resources, their inflow and temperature), the wind effect on price volatility is still persistent and significant. Adding more covariates increases the adjusted R^2: the first regression model with seasonal dummies explain 15% of the total variation in the price volatility, whereas the fifth regression model fits the data better and explains 32% of the total variation.

The finding that there is a statisitcally siginificant effect of wind on price volatility is in line wiht previous literature on the topic ([12, 31, 32]). Based on the fifth regression estimates, the main effect of wind is 0.24: if the wind power output throughout the whole Nordic region is increased by 1 TWh/month, this increases

[6] Robust standard errors of the estimates can be found in Table B.1 of Appendix B

Table 2: Regression results for price volatility in Finland

	(1)	(2)	(3)	(4)	(5)
Wind		0.26***	0.21***	0.25***	0.24**
InflowFI			0.21	0.25	0.25
Reservoir			0.01***	0.02***	0.02***
HDD				0.08***	0.08***
Trend					0.001
Jan	−2.43***	−2.81***	−2.72***	−4.29***	−4.29***
Feb	−2.35***	−2.69***	−2.61***	−4.18***	−4.17***
Mar	−2.52***	−2.86***	−2.79***	−4.09***	−4.09***
Apr	−2.50***	−2.78***	−2.72***	−3.53***	−3.53***
May	−1.83***	−2.08***	−2.02***	−2.31***	−2.31***
Jun	−1.80***	−2.03***	−1.98***	−2.03***	−2.03***
Jul	−1.84***	−2.03***	−1.99***	−2.02***	−2.02***
Aug	−2.16***	−2.37***	−2.33***	−2.37***	−2.37***
Sep	−2.22***	−2.50***	−2.44***	−2.70***	−2.70***
Oct	−2.22***	−2.55***	−2.48***	−3.28***	−3.28***
Nov	−2.51***	−2.88***	−2.80***	−3.94***	−3.94***
Dec	−1.87***	−2.30***	−2.21***	−3.66***	−3.66***
R^2	0.15	0.23	0.29	0.32	0.32
Adjusted R^2	0.09	0.17	0.23	0.26	0.26
F Statistic	153.4	157.1	147	144.3	135
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1): seasonal dummies. Column (2): seasonal dummies + wind. Column (3): seasonal dummies +wind +inflowFI +reservoir. Column (4): seasonal dummies +inflowFI +reservoir+HDD. Column (5): seasonal dummies +inflowFI +reservoir+HDD+trend. Units: inflow,reservoir and wind are measured in TWh/month. Variables "inflow" and "reservoir" are expressed as deviations from their seasonal mean values

the price volatility in Finland by 24%.

The trend component is not significant as indicated by the regression analysis and there is a good explanation to this. As we can see in Fig. 4, the trend resembles the quadratic parabola whereas the linear trend is used in the regression equation. However, as it can be seen from Table B.2 in Appendix B, using the quadratic trend instead of a linear one does not increase the significance of the trend component.

The INFLOW covariate is not statistically significant at 5% level. RESERVOIR covariate is significant but the magnitude of its effect is very small (if the amount of hydropower is increased by 1 TWh/month above its mean seasonal value, this increases the Finnish price volatility by 2%). It can be concluded that the deviations of the hydropower output from its mean seasonal value does not have a big impact on the price volatility in Finland. This is an intuitively clear conclusion as Finland does not have as much hydro resources as other Nordic countries (see Table A.1)

By reviewing the dummy variables' coefficients, one can conclude that the price volatility in Finland is higher during spring-summer months (through May-August) than it is in the rest of the year. The magnitude of the difference is, on average, around 1.7. The seasonal estimates imply that throughout May-August period, the volatility is 1.7 times higher than that from September to February. This finding coincides with the fact stated by J.Fabozzi [37] and by S.Rothe [38] and with empirical findings explored by R. Green [29] and H.Higgs et al. [30].

This particular behaviour of price volatility in different seasons can be explained in terms of how much hydropower capacity is available in summer months. The prices during heavy water inflows in spring-summer dumps the prices because of supply abundance. This abundance, in fact, decreases the hydropower station ability to adjust its supply in time. This inability of prompt adjustment leads to either supply excess or to a lack of supply, both of which interferes with electricity price stability.

4.2 Sweden

The main focus of the study is at the most northern SE1 and the most southern SE4 bidding areas. The regression results for the SE1 area are presented in Table 3.[7]

The SE1 region has the least number of territorial mergers and adjustments and it is the most stable bidding area, geography-wise. The wind covariate is not significant while the other exogenous covariates have a statistically significant effect on the Swedish price volatility. As it can be seen from the adjusted R^2, controlling for the exogenous energy supply shifters improves the model fit: the first regression with the

[7] Robust standard errors of the estimates can be found in Table B.3 of Appendix B

Table 3: Regression results for price volatility in Sweden (the SE1 area)

	(1)	(2)	(3)	(4)	(5)
Wind		0.06	−0.004	0.04	0.03
InflowSE			0.10***	0.13***	0.13***
Reservoir			0.01**	0.02***	0.02***
HDD				0.08***	0.08***
Trend					0.002
Jan	−2.62***	−2.70***	−2.61***	−4.30***	−4.28***
Feb	−2.67***	−2.74***	−2.67***	−4.35***	−4.34***
Mar	−2.93***	−3.01***	−2.93***	−4.33***	−4.33***
Apr	−2.70***	−2.75***	−2.69***	−3.56***	−3.56***
May	−2.07***	−2.12***	−2.07***	−2.37***	−2.38***
Jun	−1.93***	−1.98***	−1.93***	−1.99***	−1.99***
Jul	−2.20***	−2.24***	−2.19***	−2.22***	−2.23***
Aug	−2.59***	−2.63***	−2.58***	−2.63***	−2.64***
Sep	−2.56***	−2.62***	−2.55***	−2.83***	−2.83***
Oct	−2.57***	−2.64***	−2.57***	−3.43***	−3.42***
Nov	−2.84***	−2.92***	−2.84***	−4.07***	−4.06***
Dec	−2.51***	−2.60***	−2.50***	−4.06***	−4.05***
R^2	0.17	0.17	0.28	0.32	0.32
Adjusted R^2	0.11	0.11	0.22	0.26	0.25
F Statistic	197.4	194.9	206	203.2	190.2
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1): seasonal dummies. Column (2): seasonal dummies + wind. Column (3): seasonal dummies +wind +inflowSE +reservoir. Column (4): seasonal dummies +inflowSE +reservoir+HDD. Column (5): seasonal dummies +inflowSE +reservoir+HDD+trend. Units: inflow,reservoir and wind are measured in TWh/month. Variables "inflow" and "reservoir" are expressed as deviations from their seasonal mean values

seasonal dummies can explain only 11% of the total variation in the price volatility, whereas the fifth regression is explaining 25% of it.

The amount of water inflow to the region has the highest impact on price volatility (an increase of 1 TWh/month above its mean seasonal value results in a 13% increase in the Swedish price volatility). The absence of correlation between price volatility and wind can be seen from both Fig 7 and Table 3. One way to explain the absence of correlation is to remember the geographical position of the SE1 area: it is the most northern bidding zone in Sweden with the least wind power output capacity and the biggest share of the country's traditional generation infrastructure and, therefore, quite stable electricity prices.

Since Sweden is divided into four bidding areas and the generation mix in the northern and southern parts of the country is very different, it is necessary to consider at least one bidding zone in the northern part of Sweden and one area in its southern part. However, when the regression for the most southern bidding area of Sweden (the SE4 zone) is run, the results are very similar to those of the SE1 area (Table 4).[8] Adding the covariates keeps the wind covariate significant until the trend component is added into the fifth model. Although the trend component is not significant at 5% level, it still controls for exogenous increase in the price volatility which is not explained by other variables and thus the trend covariate should remain in the model.

The graphical analysis in Fig 7 and regression results in Table 4 suggests that there is no statistically significant impact of wind on price volatility in Sweden. One way to explain this is to remember that the recent change in bidding areas decreased price volatility and changed its trend. This artificial action aimed at improving grid's utilization have decreased price volatility and stopped its prompt growth (this can be seen in Fig. 6).

As in the case of Finland, price volatility is higher during spring-summer months (through May-August) than it is in the rest of the year. The magnitude of the difference is, on average, 1.5 : it can be said that the electricity price volatility in the SE4 area is 1.5 more volatile during spring-summer months than it is in the fall-winter season.

[8] Robust standard errors of the estimates can be found in Table B.4 of Appendix B

Table 4: Regression results for price volatility in Sweden (the SE4 area)

	(1)	(2)	(3)	(4)	(5)
Wind		0.21***	0.14**	0.18***	0.15
InflowSE			0.11***	0.13***	0.13***
Reservoir			0.01***	0.02***	0.02***
HDD				0.08***	0.08***
Trend					0.01
Jan	−2.59***	−2.89***	−2.79***	−4.39***	−4.35***
Feb	−2.53***	−2.80***	−2.71***	−4.31***	−4.27***
Mar	−2.80***	−3.08***	−2.99***	−4.32***	−4.29***
Apr	−2.64***	−2.86***	−2.79***	−3.62***	−3.61***
May	−2.04***	−2.24***	−2.18***	−2.47***	−2.48***
Jun	−1.84***	−2.03***	−1.96***	−2.02***	−2.04***
Jul	−2.12***	−2.28***	−2.23***	−2.26***	−2.28***
Aug	−2.49***	−2.67***	−2.61***	−2.66***	−2.68***
Sep	−2.52***	−2.74***	−2.67***	−2.93***	−2.94***
Oct	−2.52***	−2.79***	−2.70***	−3.52***	−3.51***
Nov	−2.67***	−2.97***	−2.87***	−4.04***	−4.02***
Dec	−2.41***	−2.76***	−2.65***	−4.12***	−4.09***
R^2	0.15	0.21	0.35	0.38	0.38
Adjusted R^2	0.09	0.15	0.29	0.33	0.32
F Statistic	197.4	194.9	206	203.2	190.2
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1): seasonal dummies. Column (2): seasonal dummies + wind. Column (3): seasonal dummies +wind +inflowSE +reservoir. Column (4): seasonal dummies +inflowSE +reservoir+HDD. Units: inflow,reservoir and wind are measured in TWh/month. Variables "inflow" and "reservoir" are expressed as deviations from their seasonal mean values

4.3 Norway

Norway is currently divided into five bidding areas amongst which the NO1 zone has the longest data set. The regression results for the NO1 area can be found in Table 5.[9]

Table 5: Regression results for price volatility in Norway (the NO1 area)

	(1)	(2)	(3)	(4)	(5)
Wind		0.20***	0.11	0.15**	0.37***
InflowNO			0.06***	0.08***	0.09***
Reservoir			0.02***	0.02***	0.02***
HDD				0.10***	0.12***
Trend					−0.05**
Jan	−3.12***	−3.41***	−3.27***	−5.30***	−5.62***
Feb	−3.15***	−3.40***	−3.28***	−5.31***	−5.59***
Mar	−3.39***	−3.65***	−3.53***	−5.22***	−5.44***
Apr	−3.22***	−3.43***	−3.33***	−4.38***	−4.44***
May	−2.58***	−2.77***	−2.68***	−3.04***	−2.95***
Jun	−2.64***	−2.82***	−2.74***	−2.79***	−2.64***
Jul	−2.40***	−2.55***	−2.48***	−2.51***	−2.32***
Aug	−3.10***	−3.27***	−3.19***	−3.24***	−3.07***
Sep	−3.37***	−3.58***	−3.48***	−3.81***	−3.73***
Oct	−3.25***	−3.51***	−3.39***	−4.42***	−4.50***
Nov	−3.33***	−3.61***	−3.48***	−4.96***	−5.14***
Dec	−3.31***	−3.63***	−3.48***	−5.36***	−5.65***
R^2	0.16	0.2	0.31	0.35	0.37
Adjusted R^2	0.11	0.14	0.25	0.29	0.31
F Statistic	244.7	235.7	236.5	234.5	225.4
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1) : seasonal dummies. Column (2): seasonal dummies + wind. Column (3) : seasonal dummies+wind+ inflowNO+reservoir. Column (4) : seasonal dummies +wind+ inflowNO+reservoir + HDD. Column (5) : seasonal dummies +wind+ inflowNO+reservoir + HDD + trend Units : inflowNO,reservoir and wind are measured in TWh/month. Variables "inflowNO" and "reservoir" are expressed as deviations from their seasonal mean values

The covariates that are specified in Equation 2 are presented in the fifth model (column 5 in Table 5): the estimates are statistically significant at 1% level and there

[9]Robust standard errors of the estimates can be found in Table B.5 of Appendix B

is a meaningful correlation between price volatility and wind power output in the NO1 area. Moreover, the wind covariate has the biggest impact on price volatility among other variables included in the fifth regression model. As it can be seen from the adjusted R^2 statistics, controlling for the exogenous supply shifters and the trend component improves the model fit and helps explaining up to 31% of total variation in the dependent variable. The results indicate that a 1 TWh/month increase in wind generation output in the whole Nordic region leads to a 37% increase in Norway's electricity price volatility. Estimated coefficients for the seasonal dummies show the same pattern as they did for Finland and Sweden: price volatility is higher during spring-summer months than that of fall-winter season. On average, the fall-winter price volatility is 2.5 times lower than it is in spring-summer. In Norway, the difference in price volatility between different seasons turns out to be higher than it is in Finland or in Sweden. One explanation for this could be that Norway has more hydro-resources than other countries do (Table A.1). In summer months, when hydro resources are in abundance, it is harder to control the energy supply from hydroelectric power stations; this can lead to either an excess or a lack of supply making electricity prices more unstable. And the effect is more profound in regions rich in hydro resources (such as Norway).

4.4 Denmark

Since Denmark is the country that has the biggest share of the wind-produced energy in its generation mix, the effect of wind on price volatility is anticipated to be the highest. The regression results for the DK1 bidding area can be seen in Table 6.[10]

As the estimates for the wind covariate indicate, the magnitude of the main effect is much higher than that for any other country in this work. Additional exogenous supply shifters do not have any significant effect on price volatility in Denmark as the wind covariate is the most influential one.

As there is no hydro resources in Denmark, the region-specific INFLOW covariate is not included into the regression model. As the RESERVOIR covariate includes

[10]Robust standard errors of the estimates can be found in Table B.6 of Appendix B

Table 6: Regression results for price volatility in Denmark (the DK1 area)

	(1)	(2)	(3)	(4)	(5)
Wind		0.86***	0.89***	0.86***	1.08***
Reservoir			−0.01	−0.02	−0.02
HDD				−0.06	−0.04
Trend					−0.05
Jan	1.03**	−0.22	−0.26	0.91	0.65
Feb	−0.74*	−1.85***	−1.89***	−0.72	−0.94
Mar	0.23	−0.88**	−0.92**	0.06	−0.11
Apr	−1.17***	−2.08***	−2.11***	−1.50*	−1.53*
May	−0.98**	−1.79***	−1.82***	−1.61***	−1.52***
Jun	−1.11***	−1.88***	−1.90***	−1.86***	−1.71***
Jul	−1.32***	−1.96***	−1.98***	−1.96***	−1.78***
Aug	−0.94**	−1.66***	−1.68***	−1.64***	−1.48***
Sep	−0.95**	−1.87***	−1.90***	−1.71***	−1.63***
Oct	−0.69	−1.78***	−1.82***	−1.22	−1.27
Nov	−0.49	−1.71***	−1.75***	−0.89	−1.03
Dec	1.05**	−0.36	−0.41	0.67	0.44
R^2	0.2	0.36	0.36	0.37	0.37
Adjusted R^2	0.15	0.31	0.31	0.31	0.31
F Statistic	5.1	8.8	8.3	7.8	7.3
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1) : seasonal dummies. Column (2): seasonal dummies + wind. Column (3) : seasonal dummies + wind + reservoir. Column (4) : seasonal dummies + wind+ reservoir + HDD. Column (5) : seasonal dummies + wind+ reservoir + HDD + trend Units : reservoir and wind are measured in TWh/month. Variable "reservoir" is expressed as deviations from its seasonal mean value

hydro-resources throughout all Nordic countries, it is used in the regression analysis, although the results suggest its effect is insignificant. The rest covariates are the same as specified in Equation 2. Based on the wind estimate, a 1 TWh/month increase in the wind power output throughout the whole Nordic market leads to a 108% increase in price volatility of the DK1 region.

Seasonal dummies indicate that there is almost no difference in Denmark's price volatility depending on a season (summer-spring or fall-winter). This should have been an anticipated result, as there is no hydro resources in Denmark: hydro-abundant months have no effect on the stability of electricity prices. The results for the DK1 bidding zone are in line with the results for the DK2 area (Table B.7).

5 Deviations from the system price

The previous section covered the question about the effect of wind on price volatility in various bidding areas throughout the Nordic region. Based on the results presented in the previous section, it is clear that an increasing share of wind-produced energy makes it harder to balance the electricity supply and demand in the day-ahead Nordic electricity market.

Additionally, there is another channel through which wind-produced energy affects the Nordic electricity market. If one investigates the evolution of gap between the system and the bidding area prices, it is obvious that it is growing, especially for countries that have a considerable share of energy produced by wind and a small amount of hydro resources at the same time. The fact that the gap is growing means that congestion restrictions are growing, as the system price is an unconstrained market clearing reference price calculated without any capacity restrictions. Quantifying the factors that contribute to the increasing gap between the system price and the bidding area prices should provide with insight on why the frequency of congestions are increasing and what bidding areas are more prone to have electricity prices that are different from the system price.

To conduct the empirical analysis for the gap between the system and bidding area prices, the following regression equation is used (3):

$$\mathrm{ln(MD)} = \sum_{\mathrm{i=1}}^{12} \mathrm{a_i D_{it}} + \beta_1 \mathrm{W} + \beta_2 \mathrm{R} + \beta_3 \mathrm{I} + \beta_4 \mathrm{HDD} + \beta_5 \gamma_{\mathrm{t}} \qquad (3)$$

$\mathrm{MD} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i=1}}^{\mathrm{n}} |\mathrm{SP_i} - \mathrm{BP_i}|$

MD is the mean of absolute differences between the system and the bidding zone's prices for a month,

SP is the system price,

BD is the bidding area price

$\mathrm{D_{it}}$ is a set of dummy variables for each month

5.1 Finland

The evolution of the gap between the system and the bidding area price in Finland is presented in Fig. 12. The trend is positive and it reveals that the system price is systematically deviate from the bidding area price. Since the most standard financial contracts traded in the Nordic region use the system price as reference price [33], this means that, de facto, those contracts will face a different electricity price. It is important that reference price reflects the actual one, that is why it is necessary to investigate what factors tend to increase this gap. The results for the regression analysis are presented in Table 7.

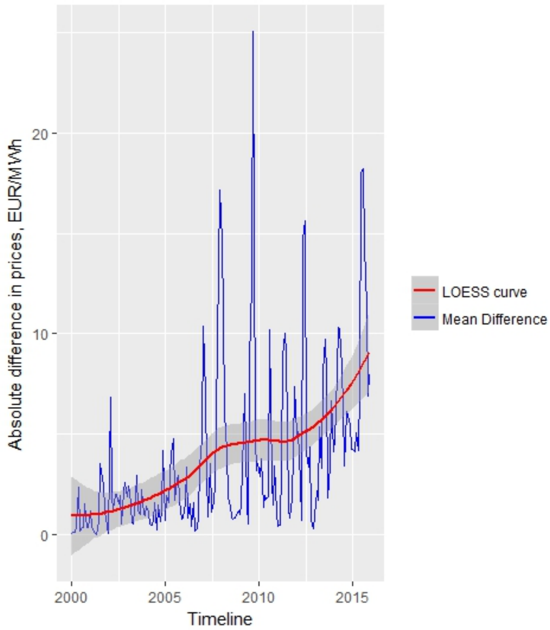


Figure 12: Mean monthly absolute differences between the system price and the area price in Finland, EUR/MWh

The estimates in the fifth column of Table 7 show that temperature and hydro-resources tend to increase the gap between the system price and the area price, but the wind covariate is insignificant when the trend covariate is added. Additionally, the seasonal dummies reveal that during the cold months (fall-winter season) the difference between the system and the bidding area price is decreasing, whereas during the warm months (spring-summer season) the estimates are either statistically insignificant or they show that the gap is increasing. Based on these findings, it

Table 7: Regression results for deviations from the mean monthly system price in Finland

	(1)	(2)	(3)	(4)	(5)
Wind		1.93^{***}	1.81^{***}	2.16^{***}	-0.22
inflowFI			0.14	0.50	0.31
Reservoir			0.05	0.08^{**}	0.08^{***}
HDD				0.68^{***}	0.54^{***}
trend					0.50^{***}
Jan	2.54^{**}	-0.24	-0.07	-13.87^{***}	-11.07^{***}
Feb	3.38^{***}	0.90	1.05	-12.72^{***}	-10.33^{***}
Mar	2.40^{**}	-0.08	0.07	-11.43^{***}	-9.56^{***}
Apr	2.53^{**}	0.51	0.63	-6.53^{***}	-6.19^{***}
May	3.37^{***}	1.55	1.66	-0.84	-1.79
Jun	3.95^{***}	2.25^{**}	2.36^{**}	1.89^{*}	0.31
Jul	4.41^{***}	2.98^{***}	3.06^{***}	2.80^{***}	0.82
Aug	6.31^{***}	4.72^{***}	4.82^{***}	4.43^{***}	2.62^{**}
Sep	5.57^{***}	3.51^{***}	3.64^{***}	1.38	0.49
Oct	3.86^{***}	1.42	1.57	-5.48^{***}	-4.92^{***}
Nov	2.04^{*}	-0.67	-0.50	-10.60^{***}	-9.11^{***}
Dec	4.06^{***}	0.90	1.09	-11.70^{***}	-9.11^{***}
R^2	0.1	0.31	0.31	0.35	0.46
Adjusted R^2	0.05	0.26	0.25	0.29	0.4
F Statistic	13.7	16.9	15	16.8	18.6
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1) : seasonal dummies. Column (2): seasonal dummies + wind. Column (3) : seasonal dummies + wind + inflowFI+ reservoir. Column (4) : seasonal dummies + wind+ inflowFI+ reservoir + HDD. Column (5) : seasonal dummies + wind+ inflowFI+ reservoir + HDD + trend Units : inflowFI, reservoir and wind are measured in TWh/month. Variables "inflowFI" and "reservoir" are expressed as deviations from their seasonal mean values

can be concluded that during warm, hydro-abundant spring-summer months the gap between price is higher than it is during fall-winter season. The higher energy output from the hydro-stations mainly located in Sweden and Norway depresses the system price during warm months. However, amount of hydro-resources in Finland is not as high as it is in Norway or Sweden and the electricity price in Finland does not fall as much as it does in the hydro-abundant regions. This makes the Finnish electricity price to deviate from the system one. As the estimates in the fifth column suggest, 1 TWh/month increase in the hydro resources energy output above the mean seasonal value increments the gap between prices by 8%. Additionally, a 1° Celsius temperature growth increases the gap by 54%. The adjusted R^2 shows that the linear regression model explains 40% of the total variation in the mean gap between the system and the area prices.

5.2 Denmark

Over time, the gap between the system price and the DK1 area's price is increasing (Fig. 13). It is worth recalling that Denmark has the biggest share of the wind-produced energy, that is why it is particularly interesting to study how the wind power affects the gap between the prices. The regression results are presented in Table 8.

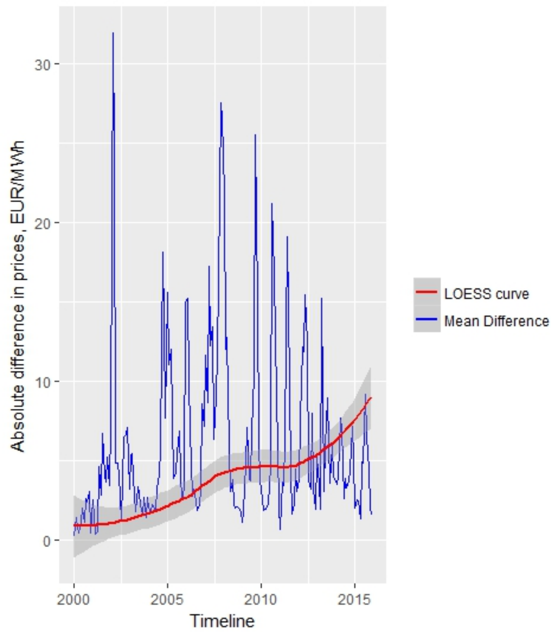


Figure 13: Mean monthly absolute differences between the system price and the area price in Denmark (DK1), EUR/MWh

The adjusted R^2 indicates that the fifth model with all the covariates listed in Equation 3 explains 16% of the total variation in the mean gap between the system and the area prices. This does not indicate a good explanatory power

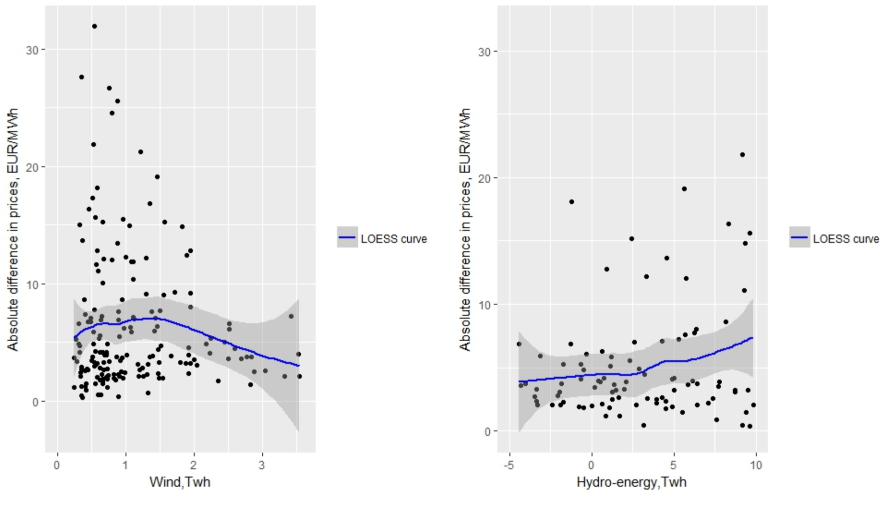
Table 8: Regression results for deviations from the mean monthly system price in Denmark

	(1)	(2)	(3)	(4)	(5)
Wind		−0.001	0.01	0.07	−0.52***
Reservoir			−0.01	−0.001	−0.001
HDD				0.10***	0.06*
Trend					0.12***
Jan	1.30***	1.30***	1.29***	−0.72	−0.04
Feb	1.17***	1.17***	1.16***	−0.84	−0.27
Mar	1.25***	1.25***	1.24***	−0.44	0.01
Apr	1.24***	1.24***	1.22***	0.18	0.26
May	1.11***	1.11***	1.10***	0.73***	0.50*
Jun	1.66***	1.66***	1.65***	1.58***	1.19***
Jul	1.47***	1.47***	1.46***	1.42***	0.93***
Aug	1.76***	1.77***	1.76***	1.69***	1.26***
Sep	1.94***	1.94***	1.93***	1.60***	1.38***
Oct	1.63***	1.63***	1.62***	0.59	0.73*
Nov	1.38***	1.38***	1.36***	−0.11	0.25
Dec	1.72***	1.72***	1.70***	−0.16	0.47
R^2	0.09	0.09	0.09	0.13	0.23
Adjusted R^2	0.03	0.02	0.02	0.06	0.16
F Statistic	45.6	41.8	38.8	38.1	41.3
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1) : seasonal dummies. Column (2): seasonal dummies + wind. Column (3) : seasonal dummies + wind + reservoir. Column (4) : seasonal dummies + wind+ reservoir + HDD. Column (5) : seasonal dummies + wind+ reservoir + HDD + trend Units : reservoir and wind are measured in TWh/month. Variable "reservoir" is expressed as deviations from its seasonal mean value of the constructed model and thus the results from the model should be treated cautiously. The estimate for the wind covariate in the fifth regression suggests that 1 TWh/month increase in the wind power output from all wind turbines in the Nordic region decreases the gap between the system and the area price by 52%. As it was concluded earlier, the DK1 area's price falls when the wind power output is increased. This, in turn, tends to decrease the gap between the system and the area price since a very significant share of wind energy is produced in Denmark. As Denmark has the biggest share of wind energy amongst the Nordic countries, it experiences an advantage that the wind brings to an electricity market: wind energy decreases electricity prices.

The effect of hydro-energy is reverse: as Denmark has literally no energy generated by hydro-resources, an increment of 1 TWh/month in the hydro-stations energy output above the mean seasonal value leads to a 6% gap increase (note, that the found effect is significant at the 10% significance level). The two opposite effects of wind and hydro energy on the difference between the system and the area price can be seen from two scatter plots presented in Fig. 14

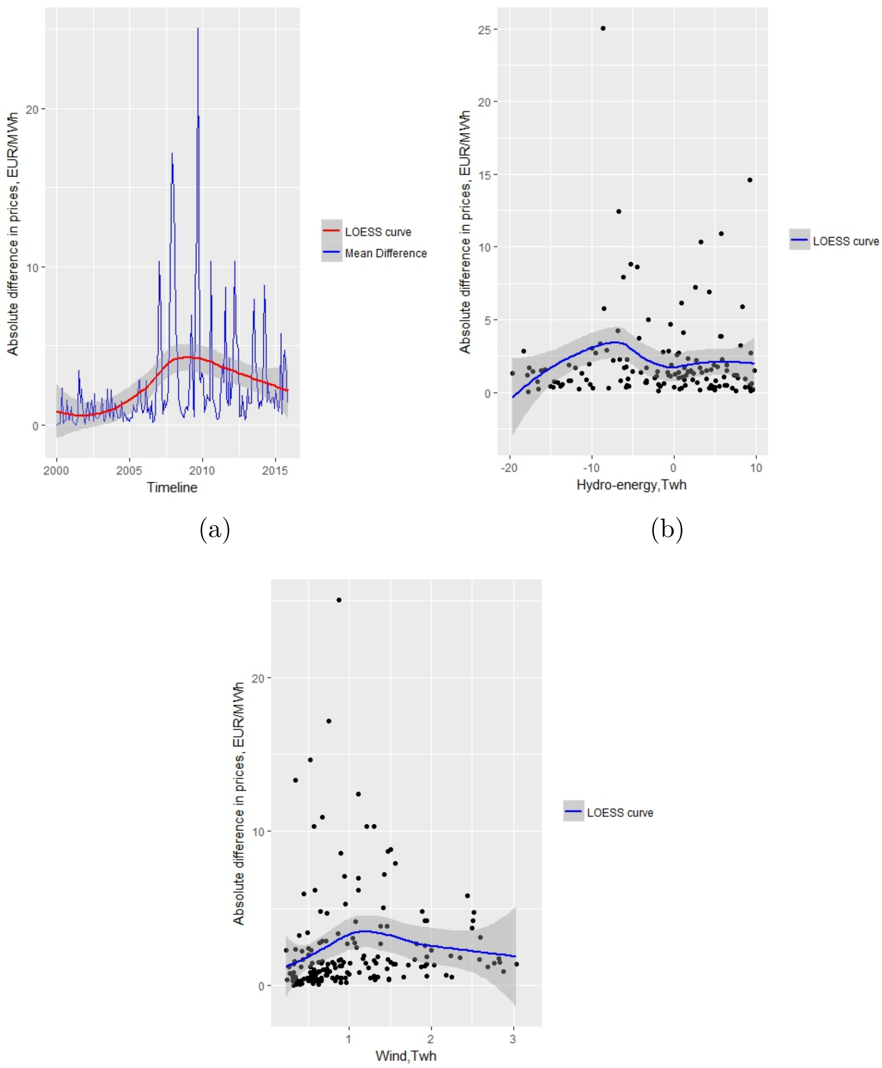


(a) (b)

Figure 14: Mean monthly differences in Denmark (EUR/MWh). (a) Mean differences and wind output. (b) Mean differences and hydro output.

5.3 Sweden

As it can be seen from Fig.15a, the gap between the system and the SE4 area's price tends to decrease staring from 2011 which is the year when Sweden was split into four different bidding zones. The only one Swedish bidding zone (SE) has been split into four areas in order to avoid energy shortages in some areas and to deal with energy excesses in the others. The graph presented in Fig.15a indicates that the split helped with converging the SE4 area's price back to the system price.



(a) (b) (c)

Figure 15: Mean monthly differences in Sweden (EUR/MWh). (a) Mean monthly differences. (b) Mean differences and hydro output. (c) Mean differences and wind output.

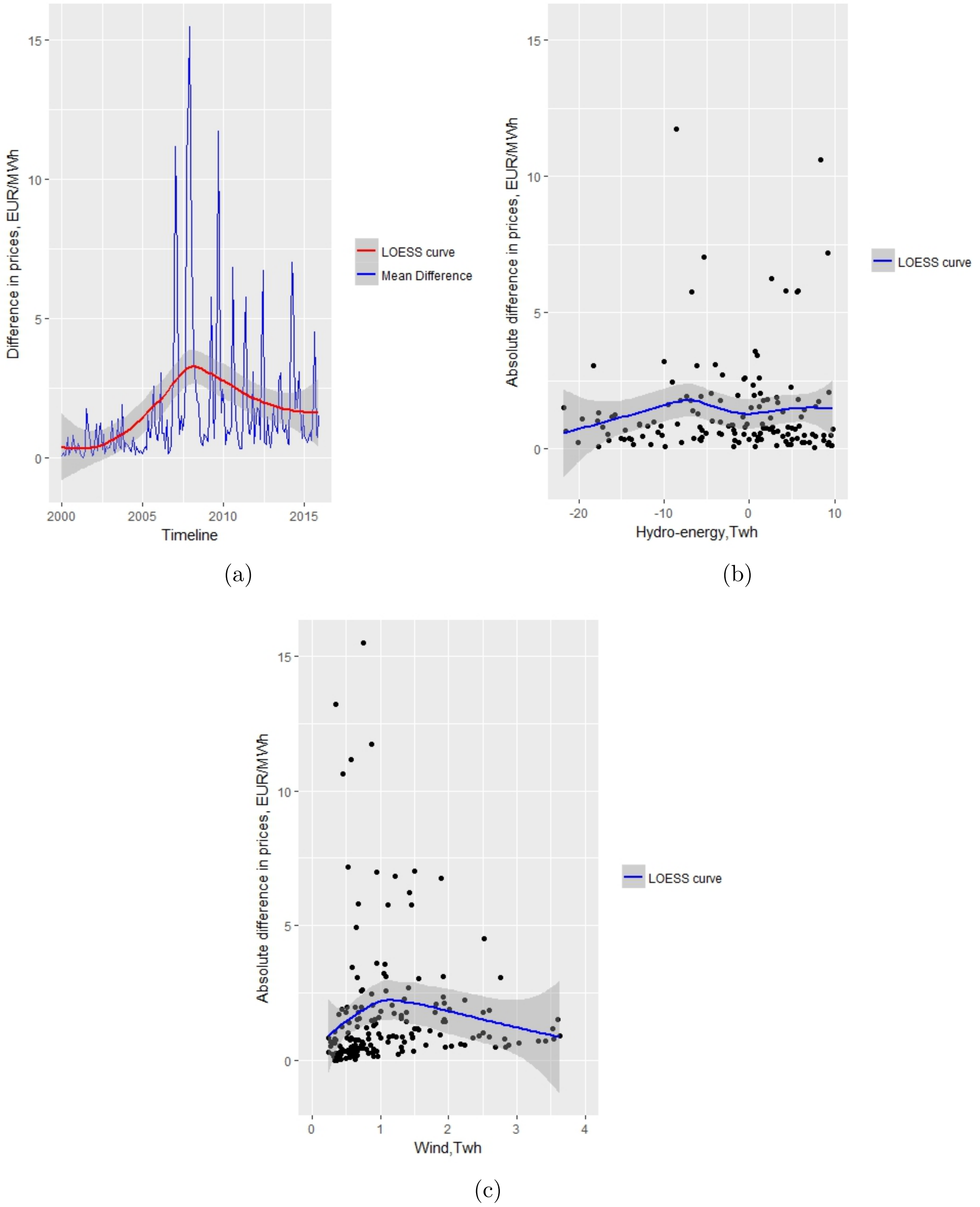
The scatter plots presented in Fig. 15b and Fig. 15c indicate that the hydro-energy output does not have a considerable effect on the absolute difference between the system and the SE4 area's price whereas the wind output decreases the gap considerably. The magnitude of these effects can be seen from the regression results presented in Table C.1 in Appendix C. Notably, an increase of 1 TWh/month in the wind production decreases the gap between the system and the SE4 area's price by 58% whereas the hydro-power output does not affect the it.

The seasonal dummies do not indicate a seasonal variation in the mean differences between the system and the area prices. Overall, the model has satisfactory explanatory power: the adjusted R^2 shows that the fifth model explains 34% of the total variation in the differences between the system and area prices.

5.4 Norway

In Norway, electricity prices in all bidding areas deviate the least from the system price compared to the other countries analysed in this work. However, the gap between the prices has slightly increased over the last sixteen years (Fig. 16a). Norway is the country that has the highest volume of hydro-energy output in the Nordic region, but deviations of hydro-resources from the mean seasonal value do not have any significant impact on the absolute difference between the system and the NO1 area's price (Fig. 16b). This finding is confirmed by the regressions estimates presented in Table C.2 of Appendix C. Notably, there is a negative correlation between the gap in prices and the wind power output (Fig. 16c). An increment of 1 TWh/month in the wind power production leads to a 71% decrease in the gap between the system and the NO1 area's price.

Based on the conducted analysis for different countries, it can be concluded that the amount of hydro-resources has literally no effect on the gap between prices in regions that are rich in hydro-energy. The wind-power output, on the contrary, tends to decrease the mean absolute difference between the system and the area's prices. Hereby, additional renewables capacity might level the system price with the area prices.



(a) (b) (c)

Figure 16: Mean monthly differences in Norway (EUR/MWh). (a) Mean monthly differences. (b) Mean differences and hydro output. (c) Mean differences and wind output.

6 Conclusion

Throughout the last 20 years, the renewable energy capacity has experienced a drastic increase. In particular, wind power energy is the first renewable energy resource to reach significant levels of introduction worldwide. While intermittently-available energy has major benefits for the society, it brings along a couple of challenges for the electricity markets. Since the nature of wind is not easily predictable, it is hard to precisely specify the amount of supply available from wind turbines in a particular hour. Both scenarios when supply is lower than anticipated and when it is higher than predicted increase inefficiencies that naturally arise in the electricity market. In this work, I examined the channels through which the wind power affects the electricity market and whether the wind energy increases the already existing inefficiencies. For studying the effect of the wind power on the electricity market, there is a need to control for supply shifters affecting the market equilibrium. For the Nordic countries, these are the amount of hydro-produced energy and temperature. Additionally, controlling for the output from hydro-resources allows to see how the wind effect differs from region to region depending on how much hydro-power is available. The main finding suggests that when the share of the wind-produced energy in the country's generation mix is increasing, this makes electricity prices more volatile. The magnitude of this effect differs across countries and the highest is in Denmark since the country has a considerable share of the wind-produced energy. The conducted analysis suggests that an increase of 1 TWh/month in the power output from wind turbines throughout all Nordic countries makes electricity prices in Denmark twice as volatile. The correlation between the wind output and the price volatility was also found in Finland and in Norway although the magnitude of the effect was smaller than that for Denmark. Notably, there was no evidence about the significant correlation between wind and price volatility in Sweden. One way to explain this is to recall that Sweden had been recently divided into four bidding zones and this event alone helped in decreasing the price volatility in each newly added pricing areas.

This finding is in line with the existing literature on daily and weekly price volatility behaviour in response to growing renewables capacity [12, 31, 32]. However, the results in this paper are different from those in the study by M.Liski and I.Vehviläinen [13] as the approaches for studying volatility differ: this work considers the actual, bidding area price of electricity instead of the system price. This change in the empirical strategy reveals that there is an impact of the increasing wind power generation on price volatility throughout the Nordic countries.

Additionally, in line with the previous literature [29, 30, 37, 38], inter-seasonal effect on electricity price volatility is found. On average, prices are more volatile in summer-spring season (throughout May - August) than they are in winter-fall period. This particular behaviour can be partially explained by the amount of hydro resources available during the year: in warm months, hydro resources are in abundance and it is harder to adjust energy supply in time. This leads to higher variance in electricity prices in summer-spring season. Notably, in the regions with more hydro resources (Sweden, Norway), this inter-seasonal effect is of bigger magnitude than in the regions with the lower hydroelectric power station output. For instance, in Denmark there is no significant difference between summer and winter in terms of electricity price volatility.

The system price and its evolution was also analysed in this work. In particular, the study was aimed at detecting the factors that affect the increasing gap between the system and the bidding area prices. Overall, it can be concluded that this gap is increasing for those bidding areas that are lacking hydro-resources and that are generating energy out of wind at the same time. The increasing gap between the system and the actual price leads to inefficiencies for those who use the system price as reference price for electricity. Since the amount of wind produced energy is constantly increasing and since wind output impacts the gap between the system and bidding area prices, there is a need for reconsidering the way the system price is calculated.

As the conducted analysis finds a significant correlation between wind capacity and price volatility, this gives a rise to the discussion about the necessity of new metering technologies introduction to the Nordic electricity market. The increasing price variance will lead to even higher allocative inefficiencies so common in an electricity market and thus will decrease the welfare if no change is introduced to the current pricing paradigm. There is already an evidence in favour of the claim that the RTP decreases price volatility: during the dry season 2002-2003, lots of households replaced the variable electricity contracts with spot based or fixed price ones [35] and based on graphical analysis of the Fig. 8, it decreased price volatility for a while. If such a change had been conducted at a bigger scale and for all households, this would have affected electricity market even more. This work clarifies that if the energy of renewable resources is to announce a new era in deregulated and clean energy sector, this should be accompanied by a new dynamic pricing paradigm.

One particular caveat of the study is that the wind-power, hydro-power output and temperature data sets are not available for each country separately, but instead are presented for all of the Nordic countries simultaneously. Hereby, this approach does not take into account the availability of the resources in each bidding area and the magnitude of the discovered effects may differ if a more granular dataset is used. However, the conducted empirical study does show that the wind power effect in price volatility exists and it depends on the region's generation mix. The fact that the wind-produced energy enhances price volatility in the electricity markets increases the importance for the discussion about the change in the current market design. The presented work points out to a lack of precise studies on how beneficial it could be to introduce alternative metering technologies into the Nordic market. The knowledge that there is a positive correlation between price volatility and wind output as well as the increasing share of energy produced by renewables make it reasonable to reconsider the current market design in favour of the RTP. Further research can be aimed at detecting benefits that arise from such a change.

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Appendix A

The data for Table A.1 and Table A.2 is obtained from the article by M.Liski and I.Vehviläinen [13].

Table A.1: Average energy generation by technology for the 2001-2015 period, TWh

Country	Hydro	Thermal	CHP	Wind	Nuclear	Total
Finland	13	12	26	0.5	22	74
Denmark	0	20	7	8	0	35
Norway	128	0	2	1	0	131
Sweden	67	1	13	4	63	148
Total	207	33	48	14	85	387

Table A.2: Wind power output (TWh/year) in Nordic countries, 2001-2015

	Year	Finland	Denmark	Norway	Sweden
	2001	0.07	4.32	0.03	0.45
	2002	0.06	4.88	0.04	0.61
	2003	0.09	5.56	0.22	0.63
	2004	0.12	6.58	0.26	0.85
	2005	0.17	6.61	0.51	0.93
	2006	0.15	6.10	0.67	0.99
	2007	0.19	7.17	0.90	1.43
	2008	0.26	6.98	0.92	2.00
	2009	0.28	6.71	0.98	2.48
	2010	0.29	7.81	0.90	3.48
	2011	0.48	9.78	1.29	6.09
	2012	0.49	10.27	1.56	7.16
	2013	0.77	11.13	1.89	9.89
	2014	1.11	13.08	2.22	11.47
	2015	2.33	14.13	2.52	16.62
Total		6.88	121.13	14.90	65.08

Appendix B

Table B.1: Standard errors of the estimates for price volatility in Finland (monthly dummies are omitted from the report)

	(1)	(2)	(3)	(4)	(5)
Wind		0.26***	0.21***	0.25***	0.24**
		(0.06)	(0.06)	(0.06)	(0.12)
inflowFI			0.21	0.25	0.25
			(0.17)	(0.16)	(0.16)
Reservoir			0.01***	0.02***	0.02***
			(0.01)	(0.01)	(0.01)
HDD				0.08***	0.08***
				(0.03)	(0.03)
Trend					0.001
					(0.02)
R^2	0.15	0.23	0.29	0.32	0.32
Adjusted R^2	0.09	0.17	0.23	0.26	0.26
F Statistic	153.4	157.1	147	144.3	135
Observations	180	180	180	180	180
Note:			*p<0.1; **p<0.05; ***p<0.01		

Table B.2: Finnish price volatility regression output with quadratic trend component in the fifth regression model (Column (5))

	(1)	(2)	(3)	(4)	(5)
Wind		0.26***	0.21***	0.25***	0.18
InflowFI			0.21	0.25	0.25
Reservoir			0.01***	0.02***	0.02***
HDD				0.08***	0.07**
QTrend					0.001
Jan	−2.43***	−2.81***	−2.72***	−4.29***	−4.17***
Feb	−2.35***	−2.69***	−2.61***	−4.18***	−4.07***
Mar	−2.52***	−2.86***	−2.79***	−4.09***	−4.00***
Apr	−2.50***	−2.78***	−2.72***	−3.53***	−3.48***
May	−1.83***	−2.08***	−2.02***	−2.31***	−2.29***
Jun	−1.80***	−2.03***	−1.98***	−2.03***	−2.03***
Jul	−1.84***	−2.03***	−1.99***	−2.02***	−2.04***
Aug	−2.16***	−2.37***	−2.33***	−2.37***	−2.38***
Sep	−2.22***	−2.50***	−2.44***	−2.70***	−2.68***
Oct	−2.22***	−2.55***	−2.48***	−3.28***	−3.22***
Nov	−2.51***	−2.88***	−2.80***	−3.94***	−3.86***
Dec	−1.87***	−2.30***	−2.21***	−3.66***	−3.55***
R^2	0.15	0.23	0.29	0.32	0.32
Adjusted R^2	0.09	0.17	0.23	0.26	0.26
F Statistic	153.4	157.1	147	144.3	135.2
Observations	180	180	180	180	180
Note:			*p<0.1; **p<0.05; ***p<0.01		

Table B.3: Robust standard errors of the estimates for price volatility in Sweden (the SE1 area, monthly dummies are omitted from the report)

	(1)	(2)	(3)	(4)	(5)
Wind		0.06	−0.004	0.04	0.03
		(0.06)	(0.06)	(0.06)	(0.12)
InflowSE			0.10***	0.13***	0.13***
			(0.03)	(0.03)	(0.03)
Reservoir			0.01**	0.02***	0.02***
			(0.005)	(0.005)	(0.005)
HDD				0.08***	0.08***
				(0.03)	(0.03)
Trend					0.002
					(0.02)
R^2	0.17	0.17	0.28	0.32	0.32
Adjusted R^2	0.11	0.11	0.22	0.26	0.25
F Statistic	197.4	194.9	206	203.2	190.2
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.4: Robust standard errors of the estimates for price volatility in Sweden (the SE4 area, monthly dummies are omitted from the report)

	(1)	(2)	(3)	(4)	(5)
Wind		0.21***	0.14**	0.18***	0.15
		(0.06)	(0.06)	(0.06)	(0.11)
InflowSE			0.11***	0.13***	0.13***
			(0.03)	(0.03)	(0.03)
Reservoir			0.01***	0.02***	0.02***
			(0.005)	(0.005)	(0.005)
HDD				0.08***	0.08***
				(0.03)	(0.03)
Trend					0.01
					(0.02)
R^2	0.15	0.21	0.35	0.38	0.38
Adjusted R^2	0.09	0.15	0.29	0.33	0.32
F Statistic	197.4	194.9	206	203.2	190.2
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.5: Robust standard errors of the estimates for price volatility in Norway (the NO1 area, monthly dummies are omitted from the report)

	(1)	(2)	(3)	(4)	(5)
Wind		0.20***	0.11	0.15**	0.37***
		(0.07)	(0.07)	(0.07)	(0.13)
InflowNO			0.06***	0.08***	0.09***
			(0.02)	(0.02)	(0.02)
Reservoir			0.02***	0.02***	0.02***
			(0.01)	(0.01)	(0.01)
HDD				0.10***	0.12***
				(0.03)	(0.03)
Trend					−0.05**
					(0.02)
R^2	0.16	0.2	0.31	0.35	0.37
Adjusted R^2	0.11	0.14	0.25	0.29	0.31
F Statistic	197.4	194.9	206	203.2	190.2
Observations	180	180	180	180	180
Note:			*p<0.1; **p<0.05; ***p<0.01		

Table B.6: Robust standard errors of the estimates for price volatility in Denmark (the DK1 area, monthly dummies are omitted from the report)

	(1)	(2)	(3)	(4)	(5)
Wind		0.86***	0.89***	0.86***	1.08***
		(0.14)	(0.14)	(0.14)	(0.28)
Reservoir			−0.01	−0.02	−0.02
			(0.01)	(0.01)	(0.01)
HDD				−0.06	−0.04
				(0.06)	(0.06)
trend					−0.05
					(0.05)
R^2	0.2	0.36	0.36	0.37	0.37
Adjusted R^2	0.15	0.31	0.31	0.31	0.31
F Statistic	197.4	194.9	206	203.2	190.2
Observations	180	180	180	180	180
Note:			*p<0.1; **p<0.05; ***p<0.01		

Table B.7: Regression results for price volatility in Denmark (the DK2 area)

	(1)	(2)	(3)	(4)	(5)
Wind		0.89***	0.88***	0.87***	0.78***
Reservoir			0.01	0.01	0.01
HDD				−0.01	−0.01
Trend					0.02
Jan	−0.35	−1.64***	−1.62***	−1.46	−1.36
Feb	−1.23***	−2.38***	−2.36***	−2.21*	−2.12*
Mar	−1.24***	−2.39***	−2.37***	−2.24**	−2.17**
Apr	−1.87***	−2.81***	−2.79***	−2.71***	−2.70***
May	−1.72***	−2.56***	−2.55***	−2.52***	−2.55***
Jun	−1.71***	−2.49***	−2.48***	−2.47***	−2.53***
Jul	−1.70***	−2.36***	−2.35***	−2.35***	−2.43***
Aug	−1.79***	−2.53***	−2.51***	−2.51***	−2.58***
Sep	−1.82***	−2.77***	−2.76***	−2.73***	−2.76***
Oct	−1.30***	−2.43***	−2.41***	−2.33***	−2.31***
Nov	−1.22***	−2.48***	−2.46***	−2.34**	−2.28**
Dec	0.10	−1.36***	−1.34***	−1.19	−1.09
R^2	0.14	0.34	0.34	0.34	0.35
Adjusted R^2	0.09	0.3	0.29	0.29	0.29
F Statistic	13.9	20.5	19.1	17.7	16.5
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1) : seasonal dummies. Column (2): seasonal dummies + wind. Column (3) : seasonal dummies + wind + reservoir. Column (4) : seasonal dummies + wind+ reservoir + HDD. Column (5) : seasonal dummies + wind+ reservoir + HDD + trend Units : reservoir and wind are measured in TWh/month. Variable "reservoir" is expressed as deviations from its seasonal mean value

Appendix C

Table C.1: Regression results for deviations from the mean monthly system price in Sweden (SE4)

	(1)	(2)	(3)	(4)	(5)
Wind		0.47***	0.49***	0.56***	−0.58***
inflowSE			−0.06	−0.02	−0.02
Reservoir			0.001	0.01	0.01
HDD				0.15***	0.08*
trend					0.23***
Jan	−0.27	−0.95***	−0.97***	−4.03***	−2.73***
Feb	−0.13	−0.73**	−0.75**	−3.81***	−2.70***
Mar	−0.41	−1.01***	−1.04***	−3.59***	−2.72***
Apr	−0.21	−0.70**	−0.72**	−2.31***	−2.16***
May	0.44	0.001	−0.02	−0.57	−1.02***
Jun	0.63*	0.21	0.20	0.10	−0.65**
Jul	0.29	−0.05	−0.07	−0.13	−1.06***
Aug	0.65**	0.26	0.25	0.16	−0.69**
Sep	0.78**	0.28	0.26	−0.24	−0.66**
Oct	0.28	−0.31	−0.34	−1.90***	−1.64***
Nov	−0.12	−0.77**	−0.80**	−3.04***	−2.34***
Dec	0.55*	−0.22	−0.25	−3.09***	−1.88**
R^2	0.1	0.18	0.19	0.23	0.4
Adjusted R^2	0.04	0.12	0.12	0.16	0.34
F Statistic	1.9	3.3	2.9	3.4	6.8
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1) : seasonal dummies. Column (2): seasonal dummies + wind. Column (3) : seasonal dummies + wind + inflowSE+ reservoir. Column (4) : seasonal dummies + wind+ inflowSE+ reservoir + HDD. Column (5) : seasonal dummies + wind+ inflowSE+ reservoir + HDD + trend Units : inflowSE, reservoir and wind are measured in TWh/month. Variables "inflowSE" and "reservoir" are expressed as deviations from their seasonal mean values

Table C.2: Regression results for deviations from the mean monthly system price in Norway (NO1)

	(1)	(2)	(3)	(4)	(5)
Wind		0.42***	0.41***	0.48***	−0.71***
inflowNO			0.01	0.05	0.03
Reservoir			−0.01	−0.002	0.0001
HDD				0.17***	0.08*
trend					0.25***
Jan	−0.32	−0.92***	−0.92***	−4.34***	−2.68***
Feb	−0.38	−0.92***	−0.92***	−4.34***	−2.87***
Mar	−0.71**	−1.25***	−1.24***	−4.10***	−2.94***
Apr	−0.46	−0.89***	−0.89***	−2.66***	−2.36***
May	0.02	−0.37	−0.37	−0.98***	−1.42***
Jun	0.02	−0.35	−0.34	−0.44	−1.23***
Jul	−0.15	−0.46	−0.46	−0.51	−1.50***
Aug	0.31	−0.04	−0.04	−0.12	−1.02***
Sep	0.50	0.05	0.05	−0.49	−0.90***
Oct	−0.13	−0.66*	−0.66*	−2.39***	−1.98***
Nov	−0.46	−1.04***	−1.04***	−3.54***	−2.60***
Dec	0.05	−0.64*	−0.63*	−3.80***	−2.26**
R^2	0.07	0.14	0.14	0.19	0.39
Adjusted R^2	0.01	0.08	0.07	0.12	0.33
F Statistic	1.3	2.3	2	2.6	6.4
Observations	180	180	180	180	180

Note: *p<0.1; **p<0.05; ***p<0.01

The table reports linear regression on the following variables. Column (1) : seasonal dummies. Column (2): seasonal dummies + wind. Column (3) : seasonal dummies + wind + inflowNO+ reservoir. Column (4) : seasonal dummies + wind+ inflowNO+ reservoir + HDD. Column (5) : seasonal dummies + wind+ inflowNO+ reservoir + HDD + trend Units : inflowNO, reservoir and wind are measured in TWh/month. Variables "inflowNO" and "reservoir" are expressed as deviations from their seasonal mean values