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THE RELATIONSHIP BETWEEN ELECTRICITY SPOT MARKET PRICES AND WIND POWER PRODUCTION: THE CASE OF ESTONIAN MARKET AREA

Bachelor's thesis

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ABSTRACT

The increasing share of renewable energy sources, one of the goals of European Union, has altered the electricity price formation. Moreover, it is suggested that the increasing renewable energy production decreases electricity prices. In order to characterize the changes concerning electricity prices, the current thesis introduces an econometric model for the hourly electricity spot prices of the Nord Pool Spot Elspot's Estonian market area with an emphasis on wind power production. The sample period covers the years 2011-2014. The estimated model includes autoregressive (AR) component and variables such as forecasted wind power production, nuclear and hydro energy production, projected electricity consumption and power transmission capacities. The results of the analysis show that wind power production slightly reduces the electricity price level and increases the volatility of electricity prices in Estonia.

INTRODUCTION

Analysis of the correlation between electricity prices and wind power generation is becoming increasingly important, as the wind energy has become one of the major sources of renewable energy. Wind energy production is supported by the governments and policy makers in North-America, Europe and China (Woo *et al* 2011). Increasing the usage of renewable energy sources is one of the goals of the European Union. Moreover, the percentage of the production of renewable energy is regulated by different acts in European Union in order to increase it. In 2007, the European Council adopted the European energy policy document COM (2007), which set the long-term goals for energy policy in the European Union. One of the goals was to increase the level of renewable energy sources by 20% for the year 2020. The directive 2009/28/EC certifies specific renewable energy targets for every member of the European Union. (Eesti taastuvenergia…) Seven years later new document COM (2014) has been adopted which has a new target to increase renewable energy usage by at least 27% by the year 2030 (Energy Efficiency…2014).

Previously studies have assessed the impact of increasing wind energy production on the level and variance of electricity prices. If the level and volatility of electricity prices are strongly affected by the wind energy production, then it is possible to draw conclusions on how the governments should act in order to promote wind energy production.

The case of the Nord Pool Spot power market is important as the Nord Pool Spot is Europe's leading power market where operate nine member countries. Elspot, which is a spot market in Nord Pool Spot, operates in Nordic and Baltic regions, and is the world’s largest day-ahead market for power trading. Moreover, Elspot is considered to be a safe, transparent and highly liquid market where the power is traded for delivery during the next day. The Elspot day-ahead market is divided into several price areas. (Nord Pool Spot)

In the current thesis Elspot’s Estonian price area will be analyzed. So far, there have not been published any econometric analysis of Nordic and Baltic region high-frequency market-price data which will be employed in this research.

The aim of the thesis is to study how the day-ahead electricity price is affected by the day-ahead wind power production. The day-ahead market will be analyzed as it is widely used and the forecasting of the day-ahead electricity price is considered to be essential to make operational decisions as accurate estimation of the price may result in remarkable financial benefit (H. Daneshi, A. Daneshi 2008).

In general, the main wind energy trading markets are based on regulated tariffs or on the exchange markets. In the given research the analysis of the electricity prices and wind energy production is mainly based on the data from Nord Pool Spot's Elspot exchange market. The hourly data from Estonia, Finland, Denmark, and Latvia will be analyzed during the period from 2011 until 2014 in order to get the most precise results.

There are two main research questions which the current thesis addresses:

1) to what extent does the wind energy production have to be increased in order to substantially decrease the electricity prices?
2) does the increasing production of wind energy affect the overall volatility of the electricity prices?

The method of analysis is based on previously conducted studies (Woo *et al* 2011; Jonsson *et al* 2010). The relevance of the following factors is being tested: wind power production, temperature, transmission capacities, emission quote prices, nuclear energy production, electricity consumption, hydro energy production, oil prices and natural gas prices.

If there is enough evidence to claim that wind power production decreases electricity prices on remarkable extent then the governments should consider finding suitable ways to further support the production of wind power. In addition, if wind energy production has a substantial effect on the electricity prices, new technologies should be developed and the risk caused by increasing wind power production should be taken into consideration (Deng, Oren 2006; Eydeland, Wolyniec 2003). Another issue which might be addressed is the lack of transmission capacity.

The thesis consists of two chapters. The first chapter covers relevant literature about the topic and different methods that enable to analyze the correlation between electricity prices and wind power production. It is also briefly explained how the Nord Pool's Elspot exchange market works. The second chapter contains empirical analysis, results and recommendations for the policy and further research.

The author thanks Nord Pool Spot and Estonian Weather Service for providing data that was needed to carry out the analysis and Finngrid for useful suggestions. The author is very greateful to her supervisor, Peeter Luikmel, for recommendations, dedication and help. The author also thanks her family and friends who are always supporting.

1. LITERATURE OVERVIEW

Several studies in different countries have been conducted about the relationship between wind energy production and electricity prices. To provide an empirical analysis on the aforementioned relationship it is possible to use different methods. It is proven that the electricity spot prices are in correlation with dynamics of renewable energy. Moreover, there is a negative correlation between the electricity prices and renewable energy production. This means that if the production of renewable energy increases, the electricity prices are going to decrease. (Sensfuß *et al* 2008)

In what follows, the overall factors constituting electricity price and the main features of empirical studies on the relationship between electricity prices and wind power production will be presented.

1.1. Determinants of electricity prices

The electricity markets have gone through liberalization during the past decades as the exchange markets for electricity trade have become substantial. This tendency has made the electricity price formation more transparent. However, different countries have political and climatical peculiarities which make energy markets around the world rather diverse. Thus, the findings for one region or country should not be generalized for others. (Ziel *et al* 2014)

Electricity is a very specific commodity as its demand is dependent on weather and business cycle. As regards to electricity price modeling, it is not possible to rely on models that are developed for financial or other commodity markets. Moreover, even small changes that occur in load or generation may cause important changes in prices. Having this said, there is no other market like the electricity market. (Huisman *et al* 2006)

Taking into consideration the economic theory of competitive markets, it is claimed that the electricity price should be equal to its marginal cost. Moreover, as certain amount of electricity is needed in any case, the demand for electricity is assumed to be inelastic (Sensfuß *et al* 2008). Electricity supply function is considered to be convex and intermittent. Due to low marginal costs and transmission peculiarities, renewable energy causes frequent variations in the shape of supply curves (Karakatsani, Bunn 2008). In addition, the electricity price is dependent on the weekday and the season of the year (Weron 2006). For example, the solar energy production is dependent on the intensity of the sunshine. Especially in regard to the analysis of northern countries, it is possible to claim that in the winter the number of sunny days is lower and inversely in the summer the amount of sunshine is higher. In addition, the demand for electricity is dependent on the working days; for example many industries use energy to run their machines during the workweek. The dependence of the weekday has been taken into consideration to model price series by using a lagged value (Kristiansen 2012). Despite this fact, the analysis of special days or phases of the day are rather rare (Ziel *et al* 2014).

Electricity price behaviour is complex and unlike other traded commodities as the price series often display periodicity, inter- and intra-day correlations, trends, positive skewness, mean reverting spikes and heavy tails (Conejo *et al* 2005; Panagiotelis, Smith 2008; Kosater, Mosler 2006). Other authors also claim that electricity price has three main characteristics – seasonality, mean-reversion and high heteroscedastic volatility which can be up to 50% on the daily scale with extreme price spikes, which are sudden extreme changes in the spot prices caused by unpredictable events or accidents (Weron 2006; Eydeland, Wolyniec 2003). The price spikes appear shortly, meaning that the prices fall back to a normal level quickly – for example due to a system failure the recovery may take one day (Huisman *et al* 2006). The electricity price can therefore be described as a combination of inelastic demand, strong dependence on highly volatile energy sources and almost impossible storability.

Furthermore, as the usage of renewable energy sources incereases globally, the dynamics of spot prices has become even more complex. The price characteristics are more extreme and the forecasting of the prices remains complicated due to the very volatile nature of the many renewable energy sources. What is more, the electricity price involves a risk as some sources of electric power are not yet efficiently storable (Knittel, Roberts 2005) or it is intricate to add renewable energies to power generation systems. Although to maintain the power system stability, there must be a constant balance between production and consumption (Weron 2006). On the other hand, fuel and gas can be stored and thus the electricity power can be considered as indirectly storable (Huisman, Kilic 2012). Energy power arbitrage over time is difficult also due to policies and restrictions on its transmission.

1.2. The relationship between electricity prices and wind power production

According to studies (e.g. Ketterer 2012), the installation of renewable energy production is capital intensive. On the other hand, the production costs are close to zero. This situation leads to a merit order effect which means that electricity producers with higher variable costs like nuclear and fossil fuel plants will be pushed out of the market and electricity prices will fall, as the renewable energy producers whose variable costs are lower can offer also a lower price. Different reasearch papers prove the existence of the merit order effect on the wind power production (Nicolosi 2010; Ray *et al* 2010). A study that covers Danish energy production also claims that the electricity prices decrease due to the merit order effect (Munksgaard, Morthorst 2008) and the same result was proved in Spain according to Saenz de Miera *et al* (2008).

If the wind power production, precisely due to the merit order effect, leads to lower electricity prices, then at first it seems to be a satisfying solution. The lower prices will be plausible for the policy makers, consumers and environmentalists who will likely support the increasing reliance on price-reducing usage of wind energy. In practical terms this leads to a situation where the initial investments for any kind of power plants start to decrease and investors will lose their interest in investing in new power plants. As a result, the power plants that produce electricity at high marginal costs, but at the same time ensure a stable supply of energy production will be threatened by the wind turbines. (Jonsson *et al* 2010) In other words, the decline in spot prices could dispel investment in thermal generation (Traber, Kemfert 2011), which in turn could lead to spot price spikes during those hours when the wind generation is low (Milstein, Tishler 2010). The increased price risk implied by the increased price variance that is the integral part of wind power generation should be hedged by the policy makers, who should invest more in risk management.

Due to the low marginal cost, wind power as a whole is a price maker (Skytte 1999; Morthorst 2003). If the wind power has a substantial share of the whole energy production, the most important short-term changes of the supply function are caused by the wind power generation. The study conducted by Ziel *et al* (2014) stated that renewable energy indeed reduces electricity price – an increase in production by 1 GWh leads to a decrease in price by 2.03 EUR/MWh. Also, when the consumption reaches its daily peak and the prices rise, the added wind power production to the system lowers the prices.

In additon to the changes in price level, the production of renewable energies also affects the price volatility. This is identified by Jonsson *et al* (2010) and Woo *et al* (2011) who point out that the greater amount of wind energy leads to lower spot prices and at the same time increases the volatility of the electricity prices. Increased wind power production excludes at certain extent the fuel price risk (Bolinger *et al* 2005; Berry 2005). However, the increased spot price variance can be explained by the decreased natural gas purchase as the natural gas is a dispatchable energy source, which means that it is possible to adjust its production according to demand, whereas wind power is a non-dispatchable and this leads to the price volatility (Green, Vasilakos 2010).

Low and volatile electricity price may change or postpone investment decisions for increasing renewable energy production. These kinds of decisions are important as the energy network's transformation is needed. In order to develop energy systems the policy makers should ensure liable electricity prices that can be forecasted. European Union and especially Germany have had a plan to increase the renewable energy share of the energy production. Ketterer (2012) stated that the regulated electricity market can stabilize the electricity price development. The price volatility decreased in Germany after the change in regulations of renewable energy production. In addition, feed-in tariffs as support mechanism for the production of renewable energy accelerates the investments to renewable sources (Keles *et al* 2012). Feed-in tariffs usually provide for a renewable electricity producer guaranteed grid access, long-term contracts and cost-based price, which is higher than the retail price, for the electricity they supply to the grid. However, the renewable energy sources that employ higher production costs also receive higher tariffs (National Renewable Energy Laboratory).

Furthermore, the investment in thermal plants, especially in countries where the power generation portfolio will be renewed, is critical for the reliability of electricity systems. The advantage of wind generation is that it can be produced fuel free, but the disadvantage is that the wind generation depends on a fuel source when the wind does not blow or when it does not blow constantly. The increasing wind power production decreased the electricity price as the wind power plants displace plants that have positive fuel costs and carbon dioxide emissions. At the same time, investments promoting wind generation come from subsidies which are usually raised from additional fees that are part of final electricity price. As a result, the prices are being pushed up. (Cosmo, Valeri 2012)

1.2.1. Methods

The relationship between electricity prices and wind energy production has been analyzed using various methods. Similarly to the previous research, the correlation analysis between electricity prices and wind power production has shown negative, but weak correlation. Mere correlation analysis does not paint a clear picture of the reducing effect of the wind power production on the electricity prices. The reason lays in the absence of other factors that influence spot price level and variance (Woo *et al* 2011). Some previous research describes the short-term dynamics of electricity spot prices by univariate time series modelling (Huisman *et al* 2006; Conejo *et al* 2005). In case of Ireland, the prior relationship was characterized with Lagrange multiplier (LM test) and feasible generalized least squares (FGLS) model as it enables to asses unknown parameters in linear regression model (Cosmo, Valeri 2012). Woo *et al* (2011) used autoregressive model (AR) which characterizes indicators that vary in time. They claimed that partial-adjustment linear regression models should enable to provide important information for making electricity procurement and risk management decisions. Their analysis was conducted in Texas and the electricity prices were found to be dependent on gas prices, nuclear energy production and seasonal factors. It was also found that the daytime and nightime price effects are not equal.

On the other hand, Karakatsani and Bunn (2008) found that the models of electricity prices including demand, fuel prices or weather, have many limits. First, the fuel prices and weather conditions affect the supply indirectly and their influence to it is non-linear. This explains why fuel prices and weather conditions are not the information that directly influences the market participants' supply and the list of factors should be complemented. Secondly, many studies analyze the average indicator or peak load averages which hide intraday price fluctuations (Huisman *et al* 2006; Longstaff, Wang 2004; Karakatsani, Bunn 2008).

Kettereri (2012) conducted the analysis about wind energy production in Germany and analyzed daily energy production and day-ahead electricity prices with a generalized autoregressive conditional heteroskedasticity model (GARCH) which enables to find the best autoregressive model in order to calculate automatic correlation, error and test the significance of the model. The study showed that the wind energy production decreased the level of wholesale electricity prices from 2006 to 2011 and increased price volatility.

Previously conducted studies have analyzed the relationship between electricity spot prices and actual wind power production (Skytte 1999; Morthorst 2003). Nevertheless, those studies focus only on linear effects of the mean behavior not on distributional effects and could therefore be considered partial. Another aspect that lays in the usage of actual measured power output is that using that data does not show wind power as a price maker on the market and this results in models that cannot be used for forecasting. Therefore, Jonsson *et al* (2010) analyzed how the day-ahead electricity spot prices are affected by day-ahead wind power forecasts in West Denmark area at Nord Pool's Elspot market, using non-parametric regression (NPR) model for hourly data. As regards to wind energy, the forecasting of wind energy production is a fast growing industry and the main aim of the research was demonstrating how the wind energy production forecasts affect the market and the electricity prices. Moreover, the wind energy, as other non-dispatchable energy sources like hydropower which cannot be adjusted subject to its demand, is usually traded based on the forecasts of the production volumes (Giebel *et al* 2003; Costa *et al* 2008). Jonsson *et al* (2010) analyzed factors that affect the mean prices, intraday variation and indicators that in turn affect the hourly electricity rate in day-ahead market. Furthermore, they chose to use the forecasted wind power production data, because in that case the wind power production can be described as the market's price-maker. The analysis showed that the relationship between wind power and spot prices exists and it is non-linear and time-dependent whereas the price fluctuations are more extreme during the day instead of night.

Looking at the longer perspective, the effects caused by renewable energy has been projected for the next two decade. Green and Vasilakos (2010) found out that for the year 2020, the electricity prices in Great Britain will be strongly affected by the wind energy production and the price volatility will increase. Table 1 below presents the summary of methods which have been used to analyze the relationship between electricity prices and wind energy production.

Table 1. Studies about the relationship between electricity prices and wind power production

Authors	Countries	Analytical models
Cosmo et al (2012)	Ireland	LM test; FGLS
J.C. Ketterer (2012)	Germany	GARCH
T. Jonsson (2010)	Denmark	NPR
Woo et al (2011)	USA	AR

Source: Review provided by author

In general, the production of wind energy sets two main challenges. First, the production from wind turbines is volatile and it is complicated to regulate it according to the demand. This explains why wind energy is not the perfect alternative for other energy sources. Another obstacle in the production of wind energy occurs because the direct storage of wind power production is not yet possible. Therefore, the production of wind energy should be largely balanced by the traditional energy sources. That leads to the overproduction of wind energy and therefore the energy may be exported at a lower price than expected. Inversely, if the production of wind energy is low but the demand for energy is high, then the electricity has to be procured with higher costs. (Ketterer 2012)

2. EMPIRICAL ANALYSIS OF THE RELATIONSHIP BETWEEN ELECTRICITY PRICES AND WIND POWER PRODUCTION

Since the 1990s the electricity markets all around the world have undergone drastic reforms which have resulted in more deregulated markets. The reason for this has been the adoption of wholesale electricity markets where energy producers and distributors trade for purchase and sale of electricity. (H. Daneshi, A. Daneshi 2008)

On the other hand, the classical spot market is not suitable for electricity trading, as the system operator needs to verify in advance that the schedule is possible and the transmission constraints will be achieved (Huisman *et al* 2006). Therefore, electricity is regularly traded on two types of markets: the power exchange or power pools and over-the-counter which is also called bilateral contracts (Weron 2008). The latter have a delivery period varying from a week up to a year and former contracts are traded on a day-ahead market with deliveries on the next day or intra-day markets with a delivery in 15 or 30 minutes after the bargain (Huisman *et al* 2006). Usually, the bids are set through a mechanism which determines a spot price at which electricity is traded. However, due to the complex nature of the wind energy, the dynamics of the spot prices are only partially understood which makes the forecasting of the spot prices rather difficult. Despite this fact, the understanding of the price dynamics and its' predictability is important for all market participants and policy makers in order to enforce better planning, trading, risk management or alternatively, market design decisions. (H. Daneshi, A. Daneshi 2008)

2.1. Overview of the Elspot electricity market

The northern countries created common Nordic market in 1990s, whereas Estonia, Latvia and Lithuania deregulated their energy markets in the late 2000s. Deregulation meant that the governments are not leading the energy market anymore and the producers and resellers trade on the market that is characterized by free competition. The aim of the deregulation was a more effective market due to the transnational trading which ensured solid power supply. This led to higher production and improved efficiency. (The power…) In addition, Nord Pool Spot power exchange is considered to be one of the oldest and most stable power markets in the world (Huisman *et al* 2006).

The current thesis uses the Elspot day-ahead electricity market data. The Elspot market is operating in Norway, Sweden, Finland, Denmark, Estonia, Latvia and Lithuania. The bids between electricity sellers and buyers are settled for the next day. By now, around 360 sellers and buyers trade at the Elspot market. Moreover, many of them are trading every day making around 2000 energy sales transactions. Daily trading is based on the assumptions made by market participants. Electricity purchasers forecasts energy needs for the next day and how much the purchaser is ready to pay for the selected volume on an hourly basis. At the same time, power sellers forecast how much energy is possible to offer for the next day and which will be the hourly price for this volume. Power purchasers and sellers add their forecasted volumes to the Elspot trading system. The deadline for adding the bids to Elspot trading system is at 12pm according to Central European time. Next, the central clearing mechanism will calculate the price and hourly prices will be announced at 12:42 according to Central European time. After that the trading will take place and since 00:00 the next day, there will be energy transmissions. Energy producers will forward the agreed amount of energy to the purchaser on an hourly basis. (Day-ahead…)

The supply and demand are the main factors in hourly price formation, but the transmission capacity is also important. As the transmission limits exist, Elspot area is divided into different price zones. Problems can occur at the spots where the energy transmission grids are connected to each other and large quantities must reach to the buyers. As a result, the prices will be different at those spots to solve the problem. Meaning, if the energy transmission power is constrained, then at certain threshold, the prices will rise to decrease the demand. However, between different price areas, the electricity flow direction is always from lower price area to the higher price area. Certain area’s spot prices are calculated in a same manner as the overall Elspot prices while counting only those bids that are made in the certain area and taking into consideration the available usage within transmission grids. Meaning that every market participant can trade only on its’ own price area. Electricity market price is volatile, because it is dependent on power plants operation, undersea cable maintenance and emergency works, border transmission capacity, storage facilities, the overall economic climate and the weather. (Monthly reports) On the other hand, it has been said that the Nordic market is not as volatile as others and has the majority of the power coming from hydro production. As a result, the demand and supply are weather dependent and the level of hydro reservoirs in Scandinavia affect the level and behavior of electricity prices. (Weron 2008)

Information about the main changes at Estonian electricity market will be covered next as the current thesis sets the focus on Estonian power market. Nord Pool Spot opened a separate price area in Estonia. From 1 April 2010 until 31 December 2012, the Estonian electricity market was therefore opened for wholesale consumers within 35%. The wholesale consumers were the companies that consumed in one consumption location more than 2 GWh of energy during one year. This means that those consumers were obliged to choose themselves energy seller. This was done on a bilateral basis or by buying directly or through a broker on the Nordic electricity exchange market in Nord Pool Spot Estonian price region. The Estonian electricity market opened fully on 1 January 2013 and all electricity consumers became free consumers. (What does...)

Next, the Estonian-Latvian border transmission capacity allocation mechanism changed on 18 June 2012 in the Nord Pool Spot trading platform. Since then the common price area for Estonia and Latvia was created – NPS ELE. The aim of that change was to increase the effectiveness of transmission capacity, especially in summer, when the transmitted power is reduced in order to ensure the reliability of systems, in accordance with the temperature. This change also reduces the risk for Estonian market participants from the generation of high price peaks which may be caused by deficient systems of Latvia and Lithuania. The condition was that if there is not enough transmission capacity to satisfy the demand, then the prices will be different. Nord Pool Spot opened at the same time price area LT in Lithuania and the Baltpool energy exchange ceased its activities as a spot market stock organizer. Since 3 June 2013, the common price area for Estonia and Latvia ELE was abolished and the separate Latvian price area NPS LV was created. (Monthly reports)

Moreover, since the 6 December 2013, the trial period of EstLink 2 sea cable, which is the second connection between the price areas in Estonia and Finalnd, began (Significant Dates...). The cable ensures a maximum transmission capacity from Estonia to Finland of 850 MW and 1000 MW from Finland to Estonia. Estonian electricity system is in addition connected with Latvia and Russia. (Development of the…)

2.2. Data Series

The empirical analysis includes time series covering the period from 03.01.2011 to 28.12.2014. The selection of the sample is constrained by the data availability. However, this sample allows for profound evaluation of the model under different conditions. The data series are collected from Nord Pool Spot, Estonian Weather Service, Finland's transmission system operator Fingrid, Finnish Energy Industries, Estonian transmission system operator Elering, Danish transmission system operator Energinet.dk and Lativa's transmission system operator Augstsprieguma Tikls.

The data used in the analysis is chosen in order to describe the relationship between electricity price and wind power. Moreover, the selection of the parameters involved in the analysis is based on the previous literature introduced in the first chapter. For instance, the forecasts of wind power and consumption in Estonia were used instead of final outputs, based on recommendations provided by Jonsson *et al* (2010). Furthermore, they chose to use the forecasted wind energy production data, because in that case the wind power can be described as the market's price-maker. They also used in their model gas prices and nuclear energy production. In current research paper, the gas prices, nuclear energy from Finland, wind power production in Denmark and oil prices will be used. As energy connection between Finland and Estonia is important (Estlink1 vs...) then the capacities from Estonia to Finland and the opposite are included in the analysis. Further, the temperature is the weather variable which has influence on the electricity prices and thus it was chosen as the exogenous variable similarly to Weron (2006). Weron, Misiorek (2008) included the temperature as an arithmethic average of the hourly temperatures of six locations in Scandinavia. In current thesis the mean of the hourly temperatures of four biggest cities in Estonia is used (Tallinn, Tartu, Narva and Pärnu). In addition, the emission quote prices are included in the analysis in order to explain their influence on the electricity price in Estonia. The amount of hydro energy in the reservoirs is an important variable for price formation according to Weron (2008) and therefore the level of hydro reservoirs in Finland, Norway and Sweden is included in the analysis. The Latvian hydro energy production will also be taken into consideration.

Finally, the series have been converted from hourly data to weekly data as some parameters involved in the model are available only on weekly basis. For example analyzing weekly data, it is possible to involve in the model hydro reservoir's data which is weekly data and at the same time can have an impact on Estonian electricity price. Converting the hourly data to weekly data also eliminates the seasonality problem in electricity consumption data which is caused due to variable intraday demand and different consumption during weekdays and weekends (e.g. Kristiansen, 2012). Converting hourly data to weekly data also eliminated the seasonality problem in data series used in the current thesis. The compendious list of independent variable data series involved in the econometric analysis is following:

- average temperature (C° in four biggest cities in Estonia);
- capacity from Finland to Estonia (MW);
- capacity from Estonia to Finland (MW);
- emission quote price (EUR/ton);
- Finland's nuclear energy (MWh);
- forecasted consumption of electricity (MWh);
- natural gas price (EUR/MMBTU);
- Latvian hydro energy production (MWh);
- the hydro reservoir level (% of maximum level in Finland, Norway and Sweden);
- oil price (EUR/bbl);
- wind power production in Denamark (MWh);
- wind power projections for Estonia (MWh).

1.3. Descriptive Analysis

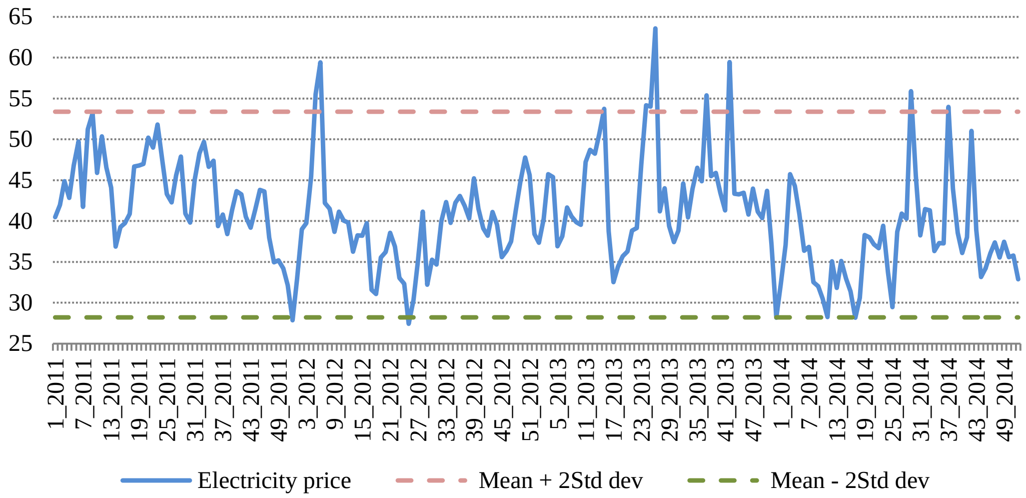
The average weekly electricity price in Estonia during the observed period was around 41 euros (see Table 2) while the minimum price was 27 euros and maximum price was around 64 euros. Meanwhile, the electricity price standard deviation was around 6 euros indicating that the price values are not very close to the mean value of electricity price. In other words, the electricity price varies from mean value during the observed period by 6 euros.

Table 2. Descriptive statistics of weekly electricity price (EUR) in 2011-2014

Electricity price	
Mean	40.78
Standard Deviation	6.32
Minimum	27.43
Maximum	63.58

Source: Nord Pool Spot

The electricity price in Estonia has shown volatility during the years 2011-2014 (see Figure 1). Moreover, the electricity price series include extreme price spikes, rapid deviations in price level, which were caused by unpredictable events and have also been detected in previous research papers (Weron 2006; Eydeland, Wolyniec 2003, Huisman *et al* 2006). However, the price spikes appear shortly and fall back to a normal level quickly (e.g. Huisman *et al* 2006). Most often, the extreme moves are related to malfunctions in the production or in the grid. High and low peaks have been identified by calculating the values that are higher or lower than the difference between mean electricity price and its double standard deviation and linking these values with the oprerational events which have had an impact on the price level (see Figure 1).



Figue 1: Weekly Electricity price in Estonia from 03.01.2011 until 28.12.2014

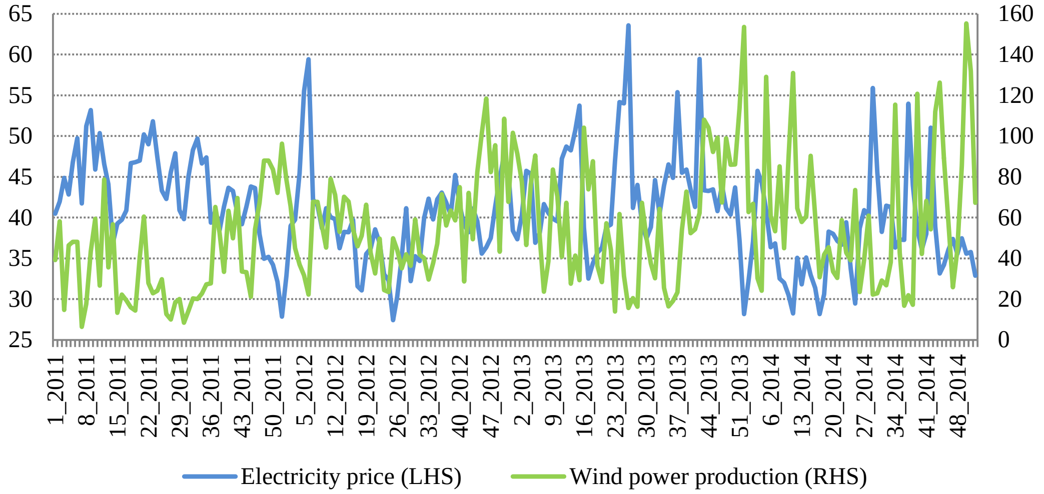
Source: Nord Pool Spot

During the observed period there have been ten high peaks. The first and the second high peak occured in 2012 during weeks 5 and 6 due to the cold weather which set the demand high for electricity in Estonia and its neighbouring countries. The high peaks were also caused due to the unplanned outages in Finland, longer maintenance duration of Sweden nuclear plant, and planned maintenance works in Estonian power plants. The third high peak occurred during the week 15 in 2013 due to the low hydro reservoirs level in Northern countries. The fourth, fifth and sixth high peak occurred in 2013 during the week 24, 25 and 26 due to the shortfall of electricity power in Latvia and Lithuania that affected the price level in the Baltics. In addition, the transmission capacity constraints from Belarus to Lithuania and constraints between Finland and Sweden affected the price. The following high peak occourred in 2013 during the week 37 due to the transmission constraints and the eighth high peak during the week 42 due to a failure of the Loviisa power plant in Finland, maintenace works in Kaliningrad plant, and transmission constraints between Lithuania to Belarus and Sweden to Finland. The ninth high peak occurred in 2014 during the week 29 due to maintenance works with EstLink 2 which led to a transmission capacity decrease between Estonia and Finland. The last high peak occurred during the week 37 in 2014 due to transmission failure from Estonia to Finland. Because of the large share of renewable energy production and low consumption in Nordic countries, the electricity price has been low in

Estonia and in the other Baltic States as EstLink 2 provides the access to lower price. (Monthly reports)

Sample period contains four low peaks. The first low peak occured in 2011 during the week 52 which represents the lowest price since Estonia started operating in the electricity exchange market. The first low peak occurred due to the significantly warm weather that led to a lower consumption than forecasted. The second low peak occurred in 2012 during the week 25 due to rainy weather which filled the hydro reservoirs to the highest level of previous three years. The third low peak occurred in 2013 during the week 52, which conjointly represents the lowest price during the year, due to holidays that cause low consumption, favorable wind conditions and warm weather. The fourth low peak occurred in 2014 during the week 17 due to the increased hydro reservoir level in Latvia. (*Ibid*)

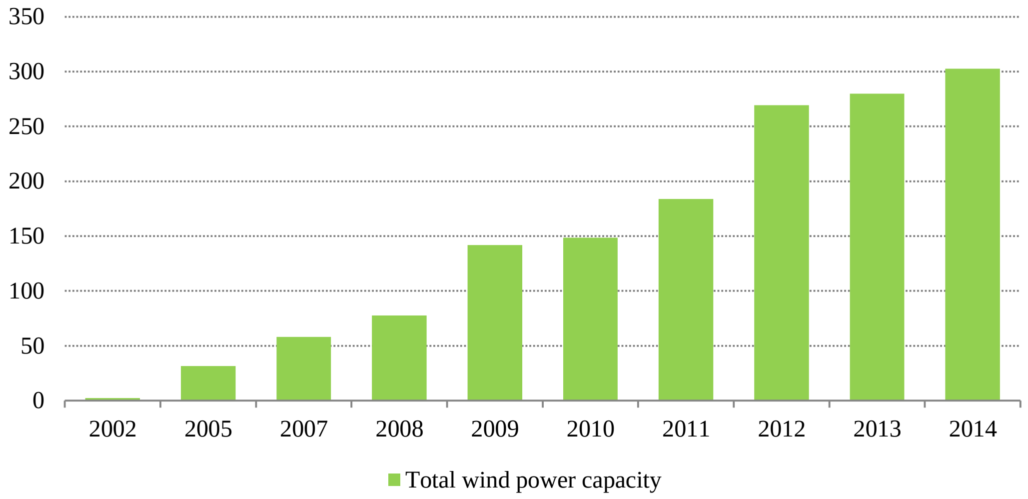
To conclude, the high peaks of electricity prices were mainly caused due to the transmission constraints and the low peaks were caused due to the high inflow of the hydro reservoirs. It is also evident that the favorable wind conditions to produce wind power have caused low electricity price levels in Estonia. As seen on Figure 2 the high electricity prices conincide with times when the wind power production is low and vice versa. The wind power production is volatile as proven in previous research papers that study renewable energy behaviour (e.g. Karakatsani, Bunn 2008).



Figue 2: Weekly electricity price (EUR) and wind power production (MWh) in Estonia from 03.01.2011 until 28.12.2014

Source: Elering, Nord Pool Spot

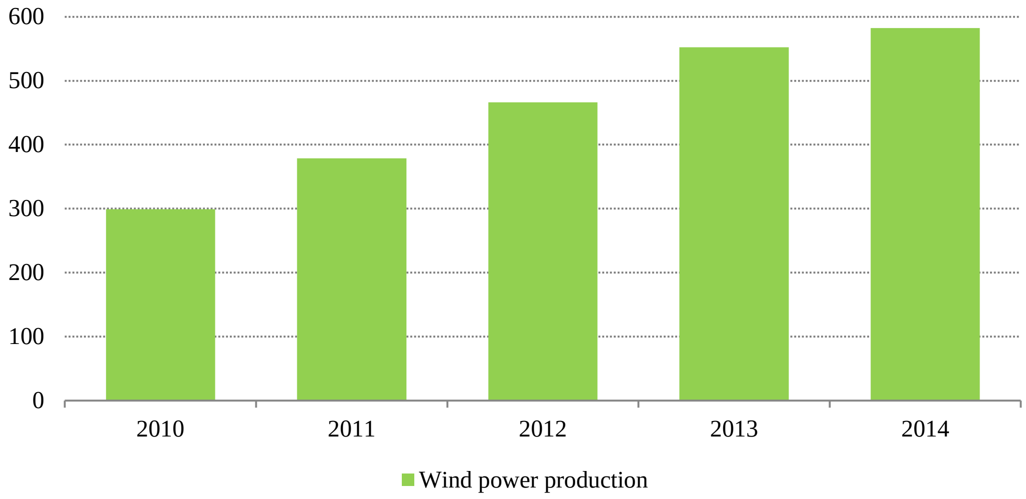
Moreover, it is possible to detect high price spikes at the time when wind power production is low, for example week 6 during the year 2012 and week 29 during the year 2014. The high price spikes caused due to the low wind power production have been detected also in previous research papers (e.g. Milstein, Tishler 2010). Likewise, it is seen from the previous graph that at the time when wind power production is high, electricity prices are low - for instance, during the week 52 in 2011 and during the week 52 in the year 2013. Former data point has been also pointed out in Elering’s monthly reports as the low price level at that time was caused due to the higher level of wind power production. Meahwhile, wind power capacity has increased in Estonia since the year 2000. The most rapid increasement was in the beginning of the 2000s and also during the years 2011 and 2012 (see Figure 3).



Figue 3: Total wind power capacity (MWh) in Estonia 2002-2014

Source: Estonian Wind Power Association

However, in the case of Estonia, wind power production is low compared to total energy output. From the year 2010 until 2014 the production of wind power has increased every year, as it is seen from the Figure 4, since the total wind power capacity has increased as well according to the previous graph. Wind power production in 2014 almost doubled compared to the year 2010 as in 2014 the production was approximately 600 GWh. In addition, in the year 2010 the wind power production was about 3% of the total energy production and in 2014 the wind power production formed 6%. (Nord Pool Spot)



Figue 4: Total wind power production (GWh) in Estonia 2010-2014, based on hourly data
Source: Nord Pool Spot

Next, the mean value and standard deviation of total projected energy production, wind production and other energy sources in Estonia that are given in MWh, are used to calculate relative standard deviation (RSD). RSD is calculated by following equation (1):

$$RSD = \frac{\sigma}{\bar{x}} 100\% \qquad (1)$$

where
σ – standard deviation,
$\bar{x}$ – mean.

RSD enables to describe the variability of wind power production in Estonia compared to other energy sources. Further, lower RSD value indicates a lower variability and higher value indicates a higher variability in data set. However, the total forecasted hourly energy production varies 20.89% during the years 2011-2014 while the hourly forecasted wind production varies 87.98% (see Table 3).

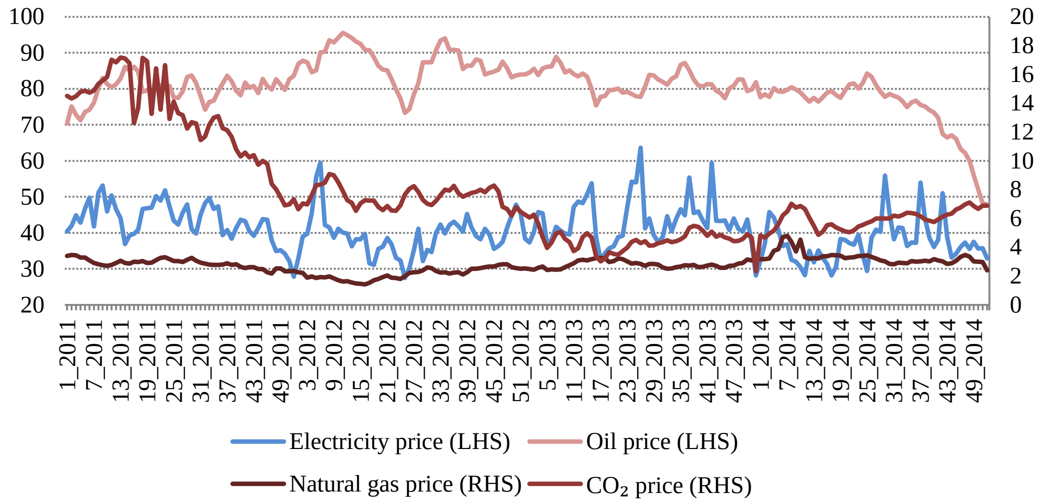
Table 3. Descriptive statistics of projections of total energy production, wind power production and other energy sources (in MWh) in 2011-2014, (based on hourly data)

Indicators	Total forecasted energy production	Forecasted wind production	Other forecasted energy sources
Mean	1265.41	54.33	1209.58
Standard deviation	264.34	47.80	267.17
RSD	20.89	87.98	22.09

Source: Nord Pool Spot, author’s calculations

Compared to other projected energy sources that vary 22% during the observed period, hourly wind power production varies around 66 percentage points more. Therefore, forecasted wind power production in Estonia refers to vary in time at a high level. On the other hand, standard deviation, which describes volatility, of forecasted wind power production is lower than the standard deviation of other forecasted energy production types. However, as the percentage of wind power production in Estonia is low compared to other energy sorces, the volatility caused by the wind power production does not destabilize the market significantly.

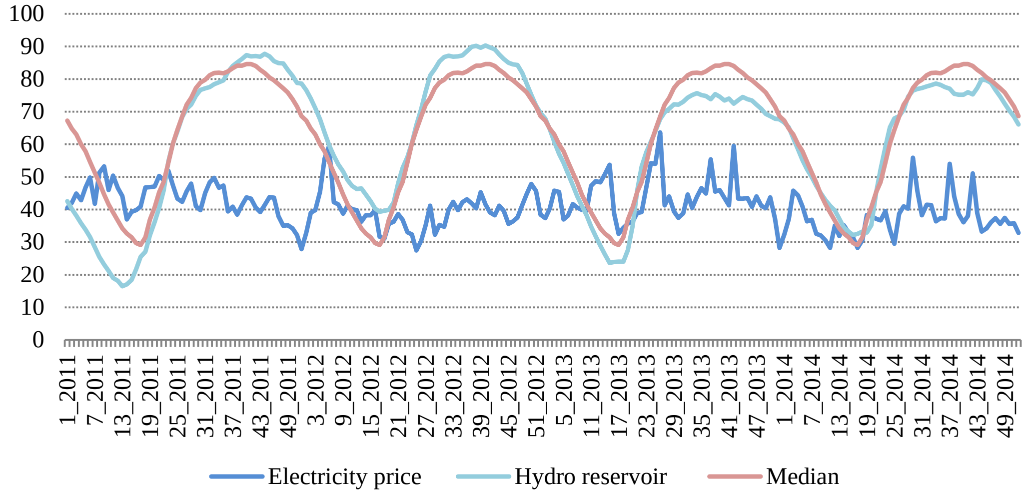
During the observed period, weekly electricity price, oil price and emission quote price, marked as a CO_2 price in the Figure 5, have been more volatile compared to gas price. Meanwhile, the gas price has been the most stable variable, CO_2 price was higher in the beginning of the observation period, next it started to decrease and it maintained the price level under 10 euros at the end of the observation period. The oil price decreased since the week 10 during the year 2012, increased since the week 24 during the year 2012, maintained afterwards more stable levels and since the week 27 in 2014 the price has shown rapid decrease.



Figue 5: Weekly electricity price in Estonia (EUR/MWh), gas price (EUR/Million Btu), CO_2 price (EUR/ton) and oil price (EUR/bbl) from 03.01.2011 until 28.12.2014

Source: Nord Pool Spot

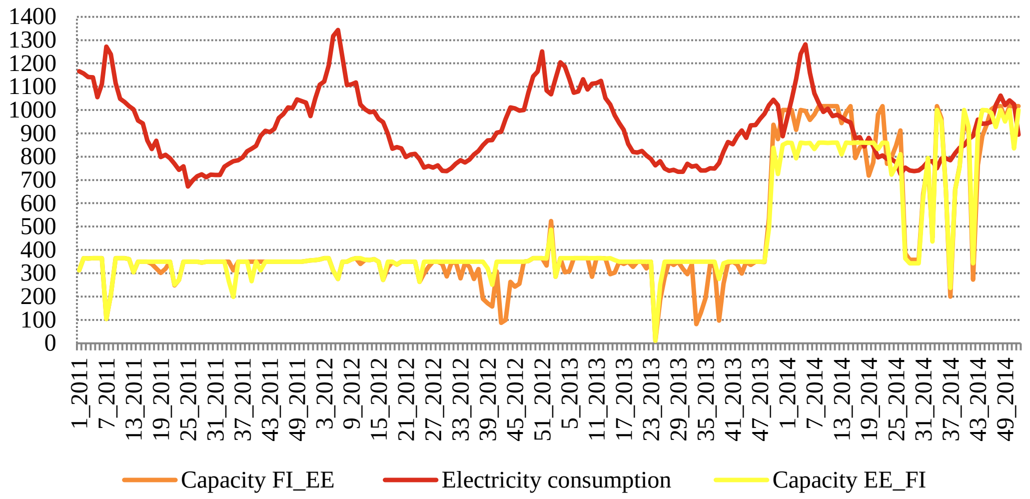
Figure 6 indicates that hydro reservoirs level shows seasonality as the reservoirs are filled the most during summer and autumn months and the level in the reservoirs is lower during winter and spring months. Due to the seasonality it is important to observe the hydo reservoirs level difference from the median value of hydro reservoirs level as this difference indicates better the impact on electricity price. It is seen from Figure 6 that if the hydro reservoir level exceeds the median level value, then the electricity prices tend to be lower. At the same time, if the hydro reservoir level value is lower than the median value, then the electricity prices tend to be higher. In addition, the highest hydro reservoir level during the sample period was at the week 40 in the year 2012 and the lowest level was at the week 13 in the year 2011.



Figue 6: Weekly electricity price in Estonia (EUR/MWh), hydro reservoir level (% of maximum level in Finland, Norway and Sweden) and hydro reservoirs median level from 03.01.2011 until 28.12.2014

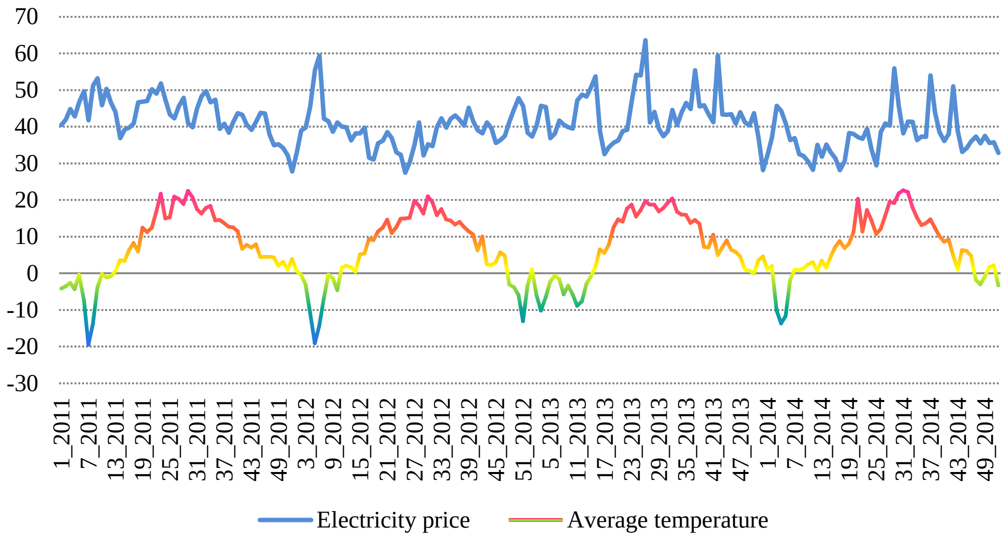
Source: Nord Pool Spot

It is seen from Figure 7 that weekly forecasted electricity consumption shows seasonality in time series as the electricity consumption is higher during winter and autumn months and lower during spring and summer months. However, capacities from Finland to Estonia and the opposite are similar and fluctuated mostly between 100 MW and 400 MW with some exceptions from the beginning of the year 2011 until December 2013, when the Estlink 2 started to operate and this in turn, led to drastic rise in capacity in both directions. The capacities increased to 1000 MW, but sudden low capacity levels that decrease to 200 MW also emerged. In other words, since Estlink 2 the capacities in both directions have been more volatile than they were before.



Figue 7: Weekly forecasted electricity consumption in Estonia and transmission capacities between Finland and Estonia and Estonia and Finland from 03.01.2011 until 28.12.2014
Source: Nord Pool Spot

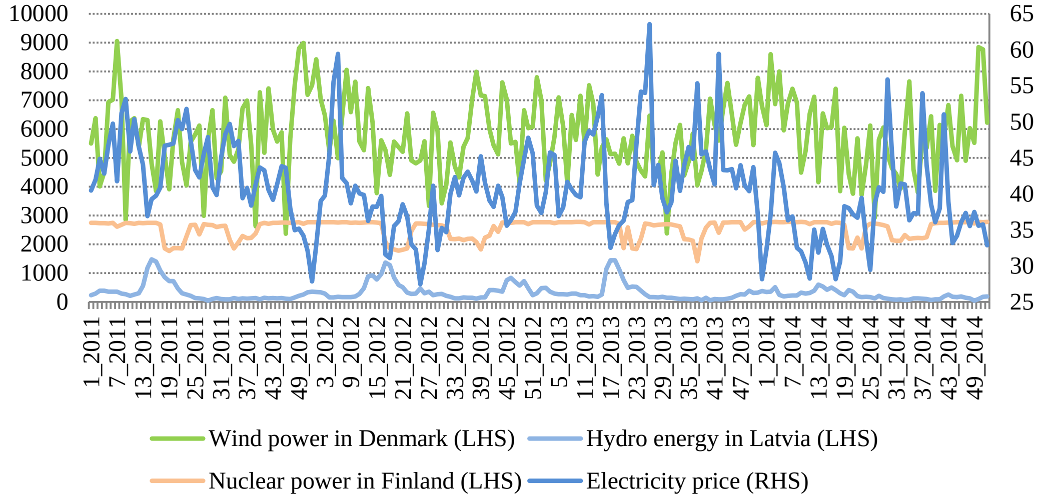
The Figure 8 indicates the relationship between electricity price and average temperature in four biggest cities in Estonia. The seasonal trend is possible to capture – when temperature is high then the prices are regularly lower. Inversely, the lower temperature level refers to higher electricity prices. The extremely cold weeks tend to cause high peaks in electricity price, while there are not many drastically low electricity price levels during the weeks when the temperature is higher than usually.



Figue 8: Weekly electricity price (EUR) and average temperature (C°) in four biggest cities in Estonia from 03.01.2011 until 28.12.2014

Source: Nord Pool Spot

Figure 9 states that wind power production in Denmark is volatile, nuclear power production in Finland and hydro energy production in Latvia on the other hand are more stable. The wind power production volumes are high in Denmark reaching up to 9000 MWh on weekly basis. However, there is no noticeable relationship between wind power production data in Denmark and electricity price data in Estonia. On the other hand, it is possible to claim that during the weeks while the nuclear energy production in Finland was low, the electricity prices in Estonia were higher. For example, the higher electricity prices and low nuclear energy production in Finland occurred during the week 23 in 2011 and during the week 37 in 2013. The highest volumes of Finnish nuclear production reached almost 3000 MWh.



Figue 9: Weekly wind power production in Denmark, nuclear power production in Finland, hydro energy production in Latvia (in MWh) and electricity price (EUR) in Estonia from 03.01.2011 until 28.12.2014

Source: Nord Pool Spot

In addition, there were weeks while the hydro energy production in Latvia was high and at the same time the electricity prices in Estonia were lower. This situation occurred for example during the week 14 in 2011, during the week 17 in 2012 and during the week 17 in 2013. The highest Latvian hydro energy values reached approximately 1500 MWh.

1.4. Econometric Analysis

To test the relationship between electricity prices and wind power production the model was estimated in regression analysis. From now on, the abbreviations of the parameters are used in econometric tests and models (see Appendix 1).

First, to determine a plausible model, the autocorrelation and partial autocorrelation coefficients were observed. Both coefficients were slowly approaching zero (see Appendix 2) and therefore it is possible to claim that the first-order autoregressive model AR (1) should be used (e.g Woo *et al* 2011). Meaning, that the output variable, electricity price is phenomenon that depends linearly on its’ own values.

Secondly, it is important to consider seasonality in time series in order to prevent undesired bias in models. If the seasonal component is ignored, then this can lead to incline in predicted values. Previously, the dummy variables have been used to model seasonality and detect unusual values in time series. The method includes a set of indicator variables to detect the seasonality (Soares, Medeiros 2008) and unusual values. Therefore, dummy variables are used in the current analysis. For instance, it is seen from the analysis of electricity price series that the variable has extreme miniumum and maxiumum values (see Figure 1). Therefore, the dummy variables that describe those high and low peaks of the electricity price were added to the model. The electricity price values that were higher than the difference between the mean value and two standard deviations, which was 53 euros, got the value 1, otherwise 0. In addition, the electricity price values that were lower than the difference between the mean value and two standard deviations, which was 28 euros, got the value 1, otherwise 0. The above-mentioned values are threshold values for dummies which were the minimum and maximum levels that were causing non-constant variance.

Thirdly, the unit root Augmented Dickey Fuller test was used to test the sationarity of time series. In some cases the test identified the non-stationarity in time series. Therefore, some data series are transformed (see Appendix 3). Following, the hydro reservoirs level parameter was modified. As stated earlier, the difference between hydro reservoirs median value and the hydro reservoirs level was calculated. The reason of this transformation was the emergence of seasonality in the data – in the autumn and winter months the reservoirs have higher levels and in the spring and summer months lower levels. Thus, the hydro power production is strongly dependent on precipitation and snow melting and this can be different from season to season (Weron *et al* 2003). The difference between median value and reservoirs level characterizes reliably how hydro energy affects the electricity price. For example, if the median value is lower than the load of hydro reservoir, then hydro energy affects the electricity price in downward direction. Inversely, if the median value is higher than the load, then the hydro energy affects the electricity price in upward direction. Therefore, the dummy variable was created which equals 1 if the hydro reservoir load is higher than the median value and 0 if the filling percentage is lower than the median value.

Next, the principal component analysis was used to decrease multicollinearity between independent variables like oil price, gas price and emission quote price. Therefore, the principal component analysis has been carried out. As a result of the transformation of above mentioned parameters, the variable was created that describes the three parameters in a single variable (see Appendix 4).

Moreover, the forecasted consumption parameter and average temperature parameter indicated non-stationarity. To eliminate that issue, the time series were modified with the moving average of two periods and by taking the first order difference respectively. The covariance analysis indicated that Latvian hydro energy and Finnish nuclear energy affect electricity price, while the factor variable does not have influence on it (Appendix 5). In addition, revealed, that the integrated average temperature and moving average of forecasted consumption caused multicollinearity (Appendix 6) in the model as average temperature is inherently a parameter that affects the progression on forecasted consumption. However, the electricity consumption forecasts usually include the effect of temperature and other variables that are related to the weather like sunshine. Therefore, forecasted consumption can be considered as more important variable describing the electricity price formation. In addition, the moving average of forecasted consumption appeared to be more significant and thus, the integrated average temperature was eliminated from the model. The problem of multicollinearity existed also between capacities from Estonia to Finland and from Finland to Estonia. However, the capacity from Finland to Estonia appeared to be more significant and as a result that variable was maintained in the model. What is more, in the end of the year 2013 the Estlink 2 transmission cable started to operate (Significant dates…). As a result, the capacity between Finland and Estonia more than doubled (Estlink1 vs…). The new connection affects the data series and causes non-stationarity. To eliminate this problem, the dummy variable was created that equals 0 before the operating of Estlink 2 and afterwards 1.

The first order difference of created single variable that decribes the oil price, gas price and emission quote price in single parameter appeared to cause multicollinearity and had too wide confidence limits, thus it was eliminated from the model. Further, wind power projections for Denmark appeared to be correlated with wind power projections in Estonia and be statistically insignificant, which implies that it does not have significant effect on Estonian electricity price. Therefore, the parameter was eliminated from the model. Following, the importance of the trend and seasons of the year were tested in the model and they appeared to be insignificant as well (see Appendix 7). After the conversions and corrections of the time series and meanwhile calculated models, the final regression model was estimated (see Appendix 8).

After the estimation of the model, the White test was performed to test the presence of heteroskedasticity which was not present according to the test (see Appendix 9). Following, the autocorrelation in the model was tested with correlogram (see Appendix 10). The results showed that the autocorrelation in given time series is not present as the probabilities of autocorrelation and partial autocorrelation coefficients are higher than 0.05. All the parameters involved in the final model appeared to be statistically significant as their probabilities were smaller than 0.05. The model explained approximately 75% of the dynamics of the electricity price formation (see Appendix 8).

In order to describe the relationship between electricity price and wind power production, the following representation of the relationship is specified (in the brackets are the standard deviations of the variables):

$$z = 44.430 - \underset{(29.8)}{0.038 WPPJ} + \underset{(148.7)}{0.009 MAEC} - \underset{(290.2)}{0.006 LHEN} - \underset{(310.3)}{0.002 FNEN} - \underset{(0.5)}{2.796 D_1} + \underset{(0.2)}{12.236 D_2} -$$

$$\underset{(0.1)}{4.312 D_3} - \underset{(0.4)}{4.803 D_4} + \underset{(6.3)}{0.481 z_{t-1}} + U_i$$

where

z = electricty price (EUR/MWh);

z_{t-1} = previous value of electricity price, AR(1) (EUR/MWh);

$WPPJ$ = wind power projections (MWh);

$MAEC$ = moving average of forecasted electricity consumption (MWh);

$LHEN$ = Latvian hydro energy (MWh);

$FNEN$ = Finnish nuclear energy (MWh);

D_1 = dummy variable for hydro reservoirs level and median value difference;

D_2 = dummy variable for electricity price’s high peak;

D_3 = dummy variable for electricity price’s low peak;

D_4 = dummy variable describing Estlink 2 operation;

U_i = residual.

The relationship shows that the electricity price decreases by 0.038 euros per MWh if the forecasted wind power production increases by one MWh. In addition, if the moving average value of the consumption increases by one MWh, the electricity price increases 0.009 euros per MWh. Latvian hydro energy has a smaller impact on price than hydro reservoirs level in

Scandinavian countries. Respectively, when hydro energy production in Latvia increases by one MWh, the electricity price decreases by 0.006 euros per MWh, while when the hydro reservoir load is higher than median value of hydro reservoirs load in Scandiavia, then the electricity price decreases 2.796 euros. The increase by one MWh of Finnish nuclear energy decreased the electricity price by 0.002 euros. Moreover, if the Eslink 2 started operating between Finland and Estonia, then the electricity price decreased by 4.803 euros. The high and low peaks affect electricity price behaviour sufficiently. Thus, the presence of the high peaks in data series is casusing electricity price increment by 12.236 euros. At the same time, if the low peaks appear in time series, then the electricity price decreases 4.312 euros. As the first order autocorrelation AR (1) coefficient equals 0.518, then the electricity price differs from its' previous value by 0.481.

In addition, it is possible to forecast the electricity price in a linear relationship while taking into consideration the European Union intention to increase renewable energy share at least to 27% by the year 2030 (European Commission 2014). Further, it is possible to assume that wind power production share will increase in Estonia from 6% to at least 15% by the year 2030 *ceteris paribus* and that the increase of wind power production by 1 MWh will decrease electricity price on average by 0.038 euros per MWh. Meaning, that by the year 2030, the average weekly wind power production will be 81 MWh compared to current volume 54 MWh. As a result, the wind power production will increase in 16 years on average 27 MWh. It is possible to claim that by the year 2030, the increase in wind power production by 1 MWh will result in a decrease of electricity price by 1.03 euros per MWh in Estonia. In that case, the savings will be on average 8 million euros based on current forecasted consumption.

Next, the question whether the forecasted wind power production has influence on the distribution of electricity prices will be answered, using similar method like Jonsson *et al* (2010). For carrying out the distribution analysis, the data series was divided into eight sections according to forecasted wind power volume and the price distribution was estimated within each section (see Table 4). Tabel 4 indicates that the lowest wind production values lie within 0-12.5% and the highest values lie within 87.5-100%.

Table 4. Weekly electricity price (EUR) distribution for eight different scenarios of forecasted wind power volume during the years 2011-2014

	Distribution by percentage range							
	0-12.5	12.5-25	25-37.5	37.5-50	50-62.5	62.5-75	75-87.5	87.5-100
Mean	45.88	44.85	40.99	40.01	39.40	40.49	38.12	37.24
Standard Deviation	5.68	7.10	6.06	6.10	5.55	6.28	4.65	5.03

Source: Nord Pool Spot, author’s calculations

According to the previous table, the highest mean electricity price value, 46 euros is present at the time while the forecasted wind power production is on the lowest level. Moreover, the mean electricity price decreases while the forecasted wind power production increases. When the wind power production has reached the highest level, the electricity price has decreased to the lowest level during the sample period. In addition, the standard deviation that shows the volatility of the electricity price is lower in the section 0-12.5% corresponding to the lowest wind power production level, but increases firmly in the next sections and stays on higher level as there is deficiency of wind power production. However, the section 87.5-100% which corresponds to the highest levels of wind power production indicates the electricity price volatility that is higher than the previous section value. Thus, it is possible to claim that lower and the highest windpower production levels cause increase in price volatility. Therefore, changes in wind power production level affect the electricity price volatility. To conclude, wind power production decreases electricity price and increases the price volatility.

CONCLUSION

The thesis focused on describing the relationship between electricity spot prices and wind power production in Nord Pool Spot Elspot’s Estonian market area during the sample period from 2011 to 2014. The aim of the thesis was to find out in which direction are the spot market electricity prices moving due to the increasing wind power production and whether the volatility of the prices is changing or not. The literature overview about studies focusing on electricity prices and wind power production were introduced and empirical estimation of prior relationship was provided.

The studies have demonstrated the determinants of electricity price formation including the wind power production influence on the prices. However, the empirical approaches have been different. Thus, the selection of the variables included in the econometric analysis and the model types have varied. The relationship between electricity prices and wind power production has been tested in numerous research papers as the wind energy has become one of the major renewable energy resources. Moreover, the recently adopted document by European Commission COM (2014) set the target to increase renewable energy usage at least to 27% by the year 2030. Currently, wind power capacities and the share of total energy production in Estonia are increasing. However, the percentage of total production is around 6%.

The model was estimated with regression analysis in order to test the relationship between electricity prices and wind power production. The seasonality was removed from the hourly data by converting the series to weekly frequency. The final estimated model contained first order autoregressive (AR) component and variables like forecasted wind power production, nuclear power production in Finland, hydro energy production in Latvia, projected moving average of electricity consumption, dummy variables denoting the operation of Estlink 2, hydro reservoirs’ level difference from median value and high and low electricity price values. The estimated stationary model indicated that the electricity price decreases by 0.038 euros per MWh if the forecasted wind power production increases by one MWh.

The volatility of electricity price caused by wind power production was captured by distribution analysis where the data series was divided into eight sections according to the level of forecasted wind power production and the price distribution was estimated within the each section. The results show higher prices during low wind power production levels and lower price during the higher level of wind power production. The higher volatility of electricity prices occurred during the lower and highest wind power production levels. Thus, the changes in wind power production cause increasing price volatility.

To conclude, there is not enough evidence to claim that wind power production decreases electricity prices in Estonia significantly. However, the decline is noticeable and if the wind power production is henceforth increasing, the influence may be more substantial in the future. Likewise, the price volatility changing due to the wind power production currently exists, but the more influential impact may be met if the wind energy production increases in the future. In general, it can be concluded that in the case of Estonia, the wind power production tends to decrease electricity price level and increase the volatility of prices.

The further research on the topic could study the future developments concerning wind power production in Estonia. In addition, if wind energy production is considered to have an important effect on the electricity prices in the future, new technologies should be developed and the risk caused by increasing wind power production should be taken into consideration. If the wind power share of the total energy production is high, then there must be spare stations that could provide energy while there is no wind. Another issue which might be addressed is the lack of transmission capacity. Increasing transparency in the energy market should enable to analyze the effect of wind power production on electricity prices more accurately.

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RESÜMEE

ELEKTRI PÄEV-ETTE TURU HINDADE JA TUULEENERGIA TOODANGU VAHELINE SEOS EESTI HINNAPIIRKONNA NÄITEL

Marge Maidla

Viimaste aastate jooksul on üle maailma kasvanud taastuvate energiaallikate kasutamine. Taastuvate energiaallikate osakaalu suurendamine kogu energiatootmises on ka üheks Euroopa Liidu eesmärgiks. 2030. aastaks on seatud eesmärk suurendada taastuvenergia toodangut vähemalt 27%-ni Euroopa Liidu elektrienergia toodangust. Lisaks on elektrienergia turud liberaliseerunud ning börsiturgude osakaal on saanud määravaks muutes elektri hinna kujunemise läbipaistvaks. Elekter on spetsiifiline kaup, mille nõudlus sõltub nii hetkeilmast, nädalapäevast, aastaajast kui ka majandustsüklist. On tõestatud, et kuna elektri vastu eksisteerib alati nõudlus, on tegemist mitteelastse kaubaga. Taastuvenergia pakkumist iseloomustavad madalad marginaalkulud ning nende võrku edastamisel esinevad piirangud. Seejuures on ilmnenud, et tuuleenergia suurenev osakaal vähendab elektri hinda ning suurendab samaaegselt hinna volatiilsust.

Käesoleva töö eesmärk on hinnata, kuidas mõjutab suurenev tuuleenergia toodang elektri hindade taset ja volatiilsust Eestis. Uurimus põhineb päev-ette turu hindade analüüsil Nord Pool Spoti Elspot turu Eesti hinnapiirkonna näitel aastatel 2011-2014. Püstitatud eesmärgi saavutamiseks testitakse ökonomeetrilise mudeli abil elektri hinda mõjutavaid tegureid Eestis ning elektri hinna volatiilsust tuuleenergia toodangu taseme kasvamisel.

Eelpool kirjeldatud seose analüüsimiseks antakse ülevaade erialasest kirjandusest ja varem läbi viidud uurimustest elektri hinna kujundavate tegurite kohta ning iseloomustatakse elektri hinna ja tuuleenergia vahelisi seoseid. Antud seost on modelleeritud erinevate riikide ja turugude põhjal. Võttes eeskujuks eelnevad uurimused, on käesoleva töö väljundiks autoregressiivne esimest järku AR (1) mudel, millesse on kaasatud tuuleenergia toodangu prognoos, Soome tuumaenergia toodang, Läti hüdroenergia toodang, libiseva keskmisega

tasandatud prognoositud elektrienergia tarbimine, fiktiivsed muutujad iseloomustamaks ekstreemselt kõrgeid ja madalaid elektri hindu, hüdroreservuaaride täituvuse erinevust mediaanväärtusest ning Estlink 2 opereerimist iseloomustav muutuja. Elektri hinda Eestis mõjutavad kõige enam ekstreemsed sündmused nagu näiteks rikked ülekandeliinides, väga külmad ilmad, soodsad tuuleolud, hüdroreservuaaride täituvus ja ülekandevõimsuse suurenemine Soome ja Eesti vahel tänu Estlink 2 opereerimisele.

Tulemused näitavad, et tuuleenergia ja elektri hindade vahel eksisteerib negatiivne kuid suhteliselt nõrk seos – elektri hind väheneb 0,038 EUR/MWh, kui tuuleenergia toodang suureneb ühe MWh võrra. Seega tuuleenergia toodang vähendab elektri hindu vähesel määral. Elektri hindade volatiilsus on analüüsi põhjal kõrgem tuuleenergia toodangu madalate väärtuste ja kõige kõrgema väärtuse korral. Küll aga ei ole volatiilsuse tõus märkimisväärselt suur. Põhjuseks võib siinkohal olla väike tuuleenergia toodangu osakaal Eestis, mis moodustab ligikaudu 6% kogu elektrienergia toodangust.

Kokkuvõttes võib järeldada, et tuuleenergiast põhjustatud elektri hinna tõus on olnud perioodil 2011-2014 madal. Küll aga eksisteerib kindel tendents, mis viitab sellele, et tuuleenergia toodangu kasvades eletrki hinnad vähenevad. Samuti on tuuleenergia mõjutanud elektri hinna kõikumist tugevalt just nendel nädalatel, kui tuult on olnud ekstreemselt palju või vähe. Seejuures, tuleb ka silmas pidada tuuleenergia salvestamise piiranguid ning üldisi ülekandeliinide võimsuste piiranguid. Eelduseks võib pidada ülekandeliinide võimsuste suurenemist ning uusi tehnoloogiaid tuuleenergia salvestamisel. Küll aga võib suurenev tuuleenergia toodangu kasv tulevikus elektri hinda rohkem mõjutada ning sellest tulenevaid riske tuleb ennetada ning luua varujaamu, mis väga madala tuule korral tuuleenergia toodangu puudumise kompenseerivad. Eeldades et tulevikus suureneb elektrituru läbipaistvus aina enam, on võimalik edaspidi uurida tuuleenergia toodangu mõju elektri hindadele täpsemalt.

APPENDICES

Appendix 1. Abbreviations and Databases

Title	Abbreviation	Database
Electricty price (EUR/MWh)	ELEC	Nord Pool Spot
Dummy variable for electricity price's high peak	D_2	
Dummy variable for hydro reservoirs load from median value	D_1	
Dummy variable for electricity price's low peak	D_3	
Dummy variable for Estlink2	D_4	
Hydro reservoir's load (MWh)	HYDR	Nord Pool Spot
Latvian hydro energy (MWh)	LHEN	Augstsprieguma Tikls
Wind power prognosis for Estonia (MWh)	WPPJ	Elering
Capacity from Estonia to Finland (MW)	EE_FI	Nord Pool Spot
Difference from capacity from Estonia to Finland (MW)	DEE_FI	
Capacity from Finland to Estonia (MW)	FI_EE	Nord Pool Spot
Difference from capacity from Finland to Estonia (MW)	DFI_EE	
Factor variable	FACT	
Difference from factor variable	DFACT	
Forecasted consumption (MWh)	CONS	Nord Pool Spot
Average temperature (°C)	TEMP	Estonian weather service
Moving average of forecasted electricity consumption (MWh)	MAEC	Nord Pool Spot
Finland's nuclear energy (MWh)	FNEN	Finngrid
Wind power prongosis for Denamark (MWh)	DENW	Energinet.dk
Difference of temperature	DTEMP	
Oil price (EUR/bbl)	OIL	Bloomberg
Gas price (EUR/MMBTU)	GAS	EIA
Emission quote price (EUR/ton)	CO2	ICE

Appendix 2. Model estimation

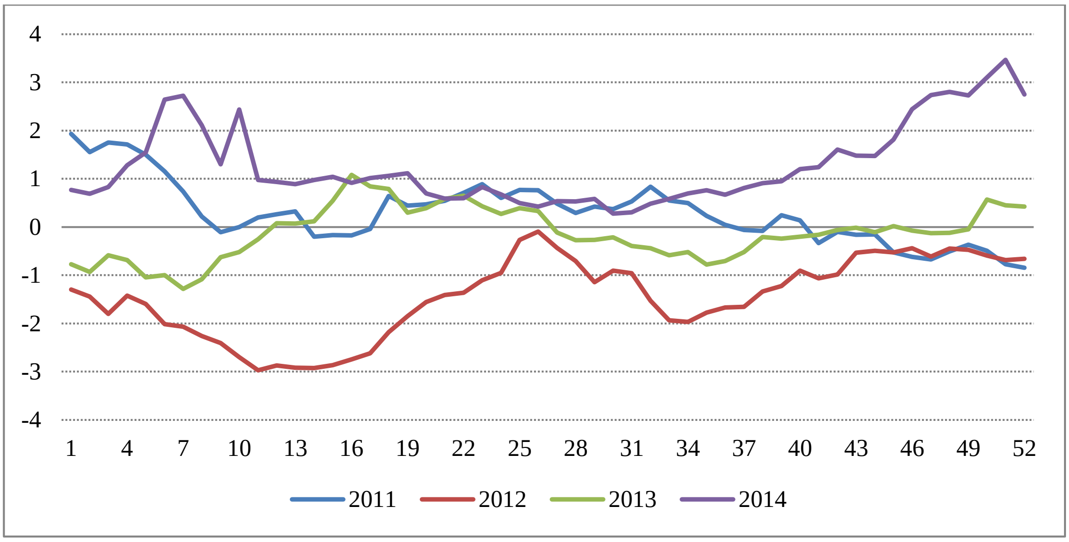
```
Sample: 1/03/2011 12/22/2014
Included observations: 208
==================================================================
Autocorrelation  Partial Correlation      AC     PAC   Q-Stat  Prob
==================================================================
      .|***  |        .|***  |         1  0.405  0.405  34.631  0.000
      .|*    |        .|.    |         2  0.209  0.053  43.866  0.000
      .|*    |        .|*    |         3  0.167  0.079  49.842  0.000
      .|*    |        .|.    |         4  0.077 -0.028  51.117  0.000
      .|.    |        .|.    |         5  0.054  0.016  51.754  0.000
      .|.    |        *|.    |         6 -0.018 -0.066  51.823  0.000
      .|.    |        .|.    |         7 -0.032 -0.012  52.040  0.000
      .|.    |        .|.    |         8 -0.040 -0.024  52.391  0.000
      .|.    |        .|.    |         9  0.006  0.052  52.400  0.000
      .|.    |        .|.    |        10 -0.004 -0.014  52.403  0.000
      .|*    |        .|*    |        11  0.083  0.114  53.949  0.000
      .|*    |        .|.    |        12  0.091  0.023  55.805  0.000
      .|.    |        .|.    |        13  0.009 -0.060  55.824  0.000
      .|.    |        .|.    |        14 -0.019 -0.048  55.904  0.000
      *|.    |        *|.    |        15 -0.124 -0.136  59.405  0.000
      *|.    |        .|.    |        16 -0.124 -0.040  62.884  0.000
      .|.    |        .|.    |        17 -0.061  0.041  63.742  0.000
      .|.    |        .|.    |        18 -0.023  0.052  63.867  0.000
      *|.    |        .|.    |        19 -0.068 -0.048  64.924  0.000
      *|.    |        *|.    |        20 -0.104 -0.070  67.422  0.000
      *|.    |        .|.    |        21 -0.072 -0.023  68.633  0.000
      .|.    |        .|.    |        22 -0.020  0.019  68.732  0.000
      .|.    |        .|.    |        23 -0.032 -0.046  68.968  0.000
      .|.    |        .|.    |        24 -0.047 -0.014  69.499  0.000
      .|.    |        .|.    |        25 -0.037 -0.002  69.832  0.000
      *|.    |        *|.    |        26 -0.111 -0.085  72.763  0.000
      .|.    |        .|.    |        27 -0.060  0.047  73.636  0.000
      .|.    |        .|*    |        28  0.033  0.089  73.899  0.000
      .|.    |        .|.    |        29  0.013 -0.023  73.938  0.000
      .|.    |        *|.    |        30 -0.032 -0.079  74.184  0.000
      .|.    |        .|.    |        31  0.039  0.071  74.552  0.000
      .|.    |        .|.    |        32  0.018 -0.015  74.630  0.000
      *|.    |        *|.    |        33 -0.066 -0.095  75.724  0.000
      .|.    |        .|.    |        34  0.015  0.070  75.781  0.000
      .|.    |        .|.    |        35  0.039  0.037  76.164  0.000
      .|.    |        .|.    |        36  0.025 -0.023  76.319  0.000
==================================================================
```

Appendix 3. Stationarity test

Variable	Augmented Dickey-Fuller test statistic	First difference
ELEC	-6.52*	
CONS	-3	-11.13*
FI_EE	-1.73*	-12.03*
EE_FI	-1.16	-12.33*
FNEN	-5.3	
GAS	-2.50*	-14.95*
LHEN	-5.3	
OIL	-0.38*	-11.80*
WPPJ	-8.37	
TEMP	-2.92*	-13.83*
DENW	-11.11*	
FACT	-1.36	-13.63*
CO_2	-2.03	-11.35*
HYDR	-4.11*	

Note: * indicates that the null hypothesis of the unit root is rejected at 1%, 5% and 10% significance level

Appendix 4. Factor variable values during the years 2011-2014



Source: Nord Pool Spot

Appendix 5. Covariance matrix

	DEE_FI	DFI_EE	MAEC	WPPJ	DENW
DEE_FI	15728.76				
DFI_EE	12764.17	13010.75			
MAEC	635.79	370.73	22110.76		
WPPJ	499.48	495.41	1537.43	889.84	
DENW	7677.99	5799.33	73127.27	16393.58	1719414.67
LHEN	-30.85	-256.61	5812.64	455.07	-28436.68
FNEN	817.39	1136.52	23442.42	3012.81	97377.73
DTEMP	16.23	29.44	73.96	-6.07	-160.80
DFACT	-0.28	0.06	-0.77	0.53	-3.40
ELEC	-81.25	-73.80	21.78	-72.34	-975.36

	LHEN	FNEN	DTEMP	DFACT	ELEC
DEE_FI					
DFI_EE					
MAEC					
WPPJ					
DENW					
LHEN	84216.16				
FNEN	-1163.49	96292.90			
DTEMP	111.37	34.21	12.94		
DFACT	1.69	-6.40	0.00	0.08	
ELEC	-464.43	-329.26	1.66	0.00	39.77

Appendix 6. Correlation matrix

	ELEC	DEE_FI	DFI_EE	MAEC	WPPJ	DENW	LHEN
ELEC	1						
DEE_FI	-0.1	1					
DFI_EE	-0.1	0.89	1				
MAEC	0.02	0.03	0.02	1			
WPPJ	-0.38	0.13	0.15	0.35	1		
DENW	-0.12	0.05	0.04	0.38	0.42	1	
LHEN	-0.25	0	-0.01	0.13	0.05	-0.07	1
FNEN	-0.17	0.02	0.03	0.51	0.33	0.24	-0.01
DTEMP	0.07	0.04	0.07	0.14	-0.06	-0.03	0.11
DFACT	0	-0.01	0	-0.02	0.06	-0.01	0.02
D4	-0.32	0.04	0.03	-0.02	0.2	0.04	-0.19
D1	-0.34	-0.06	-0.04	0.04	0.11	0.06	0.1
D2	0.56	-0.12	-0.11	-0.02	-0.17	-0.09	-0.11
D3	-0.29	0.05	0.06	-0.02	0.13	0.1	0.04

ELEC	FNEN	DTEMP	DFACT	D4	D1	D2	D3
DEE_FI							
DFI_EE							
MAEC							
WPPJ							
DENW							
LHEN							
FNEN							
DTEMP	1						
DFACT	0.03	1					
D4	-0.07	0	1				
D1	0.07	-0.01	0.12	1			
D2	-0.03	-0.07	-0.09	-0.16	1		
D3	-0.07	0.14	0.01	-0.03	-0.06	1	
	0.08	-0.08	0.08	0.07	0.09	-0.03	1

Appendix 7. Seasonality and trend test of the model

Dependent Variable: ELECTRICITY_PRICE
Method: Least Squares
Sample (adjusted): 1/17/2011 12/22/2014
Included observations: 206 after adjustments
Convergence achieved after 13 iterations

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	44.03097	5.415121	8.131116	0.0000
D_2	12.40168	1.132538	10.95034	0.0000
D_3	-4.530347	1.541553	-2.938820	0.0037
LHEN	-0.006397	0.001482	-4.317505	0.0000
D_1	-3.010528	0.785245	-3.833870	0.0002
MAEC	0.010238	0.004540	2.255243	0.0252
WPPJ	-0.035272	0.009978	-3.535073	0.0005
FNEN	-0.002282	0.001164	-1.960552	0.0514
D4	-3.270491	1.491078	-2.193373	0.0295
@TREND	-0.016409	0.011885	-1.380581	0.1690
@QUARTER=2	0.848174	1.528176	0.555024	0.5795
@QUARTER=3	0.832226	1.685783	0.493673	0.6221
@QUARTER=4	0.416554	1.265172	0.329247	0.7423
AR(1)	0.463789	0.070250	6.601961	0.0000

R-squared	0.745235	Mean dependent var	40.77271
Adjusted R-squared	0.727986	S.D. dependent var	6.345663
S.E. of regression	3.309580	Akaike info criterion	5.297061
Sum squared resid	2103.037	Schwarz criterion	5.523227
Log likelihood	-531.5973	Hannan-Quinn criter.	5.388530
F-statistic	43.20284	Durbin-Watson stat	2.045077
Prob(F-statistic)	0.000000		

Inverted AR Roots	.46

Appendix 8. Final estimated model

Dependent Variable: ELECTRICITY_PRICE
Method: Least Squares
Sample (adjusted): 1/17/2011 12/22/2014
Included observations: 206 after adjustments
Convergence achieved after 10 iterations

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	44.43038	3.312783	13.41180	0.0000
MAEC	0.009124	0.003150	2.896209	0.0042
D_2	12.23586	1.103955	11.08365	0.0000
D_3	-4.319914	1.511750	-2.857558	0.0047
WPPJ	-0.037876	0.009450	-4.008090	0.0001
D_1	-2.795877	0.779129	-3.588467	0.0004
LHEN	-0.006059	0.001324	-4.577172	0.0000
FNEN	-0.002362	0.001148	-2.058501	0.0409
D_4	-4.803126	1.001779	-4.794595	0.0000
AR(1)	0.481266	0.066556	7.230986	0.0000

R-squared	0.742399	Mean dependent var	40.77271
Adjusted R-squared	0.730570	S.D. dependent var	6.345663
S.E. of regression	3.293818	Akaike info criterion	5.269298
Sum squared resid	2126.451	Schwarz criterion	5.430845
Log likelihood	-532.7377	Hannan-Quinn criter.	5.334633
F-statistic	62.76297	Durbin-Watson stat	2.054653
Prob(F-statistic)	0.000000		

Inverted AR Roots	.48

Appendix 9. White test

Heteroskedasticity Test: White

F-statistic	0.470478	Prob. F(9,196)	0.8932
Obs*R-squared	4.356226	Prob. Chi-Square(9)	0.8864
Scaled explained SS	5.154297	Prob. Chi-Square(9)	0.8207

Test Equation:
Dependent Variable: RESID^2
Method: Least Squares
Sample: 1/17/2011 12/22/2014
Included observations: 206
Collinear test regressors dropped from specification

Variable	Coefficien t	Std. Error	t-Statistic	Prob.
C	6.554799	5.032954	1.302376	0.1943
GRADF_02^2	4.63E-06	1.59E-05	0.291074	0.7713
GRADF_03^2	3.112755	6.390661	0.487079	0.6267
GRADF_04^2	-3.472035	8.571078	-0.405087	0.6859
GRADF_05^2	-0.000962	0.000549	-1.752369	0.0813
GRADF_06^2	0.796034	5.795162	0.137362	0.8909
GRADF_07^2	3.03E-07	7.98E-06	0.037912	0.9698
GRADF_08^2	1.78E-06	2.58E-06	0.689724	0.4912
GRADF_09^2	7.033528	9.020683	0.779711	0.4365
GRADF_10^2	0.011164	0.059964	0.186187	0.8525

R-squared	0.021147	Mean dependent var	10.32258
Adjusted R-squared	-0.023801	S.D. dependent var	16.73017
S.E. of regression	16.92810	Akaike info criterion	8.543153
Sum squared resid	56165.86	Schwarz criterion	8.704700
Log likelihood	-869.9447	Hannan-Quinn criter.	8.608488
F-statistic	0.470478	Durbin-Watson stat	1.945467
Prob(F-statistic)	0.893227		

Appendix 10. Autocorrelation test

```
Sample: 1/17/2011 12/22/2014
Included observations: 206
Q-statistic
probabilities
adjusted for 1
ARMA term(s)
==========================================================================
 Autocorrelation  Partial Correlation        AC     PAC    Q-Stat   Prob
==========================================================================
     .|.    |          .|.    |          1 -0.033 -0.033  0.2299
     .|.    |          .|.    |          2  0.019  0.018  0.3032  0.582
     .|.    |          .|.    |          3  0.071  0.073  1.3814  0.501
     .|.    |          .|.    |          4  0.030  0.035  1.5765  0.665
     .|*    |          .|*    |          5  0.138  0.138  5.6299  0.229
     *|.    |          *|.    |          6 -0.092 -0.090  7.4275  0.191
     .|.    |          .|.    |          7  0.061  0.048  8.2374  0.221
     .|.    |          .|.    |          8 -0.047 -0.065  8.7110  0.274
     .|.    |          .|.    |          9  0.022  0.023  8.8163  0.358
     .|.    |          .|.    |         10  0.066  0.049  9.7752  0.369
     *|.    |          .|.    |         11 -0.077 -0.047  11.067  0.352
     .|*    |          .|*    |         12  0.190  0.173  19.066  0.060
     *|.    |          .|.    |         13 -0.070 -0.055  20.154  0.064
     .|.    |          .|.    |         14  0.056  0.045  20.853  0.076
     .|.    |          .|.    |         15  0.006 -0.025  20.862  0.105
     .|.    |          .|.    |         16  0.007  0.024  20.871  0.141
     .|.    |          *|.    |         17 -0.013 -0.080  20.910  0.182
     *|.    |          .|.    |         18 -0.079 -0.029  22.341  0.172
     .|.    |          *|.    |         19 -0.022 -0.077  22.456  0.212
     .|.    |          .|.    |         20 -0.056 -0.021  23.188  0.229
     *|.    |          *|.    |         21 -0.066 -0.076  24.203  0.234
     .|.    |          .|.    |         22  0.008  0.018  24.219  0.283
     .|*    |          .|*    |         23  0.075  0.128  25.544  0.272
     .|.    |          .|.    |         24 -0.003 -0.026  25.546  0.323
     .|.    |          .|.    |         25 -0.007  0.037  25.559  0.376
     .|.    |          .|.    |         26  0.008 -0.030  25.572  0.431
     .|.    |          .|.    |         27 -0.018 -0.020  25.652  0.482
     .|.    |          .|.    |         28  0.066  0.034  26.685  0.481
     .|.    |          .|.    |         29  0.030  0.067  26.904  0.523
     *|.    |          *|.    |         30 -0.090 -0.095  28.861  0.472
     .|*    |          .|*    |         31  0.101  0.149  31.360  0.398
     .|.    |          *|.    |         32 -0.059 -0.089  32.223  0.406
     .|.    |          .|.    |         33 -0.004  0.022  32.227  0.456
     .|.    |          .|.    |         34 -0.009 -0.025  32.249  0.504
     .|.    |          .|.    |         35  0.023  0.014  32.379  0.547
     .|.    |          .|.    |         36  0.067  0.056  33.524  0.539
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```