University of Economics in Prague

Faculty of Economics and Public Administration

Major: Economic Analysis

THE ANALYSIS OF PRICE JUMPS ON ELECTRICITY MARKET: CASE STUDY OF THE CZECH REPUBLIC

Diploma thesis

Author: Aleš Vokolek
Supervisor: Ing. Aleš Rod
Year: 2014

Hereby, I declare that I wrote my diploma thesis by myself and I used the literature and other sources which are properly listed in the enclosed references.

Aleš Vokolek
In Milovice, 20th July 2014

Acknowledgements

I am particularly grateful for the assistance given by Ing. Aleš Rod and his patience with me.

The Assignment Form

Vysoká škola ekonomická v Praze **Národohospodářská fakulta**
Katedra ekonomie **2013/2014**

ZADÁNÍ DIPLOMOVÉ PRÁCE

Autor práce: Mgr. Aleš Vokolek
Studijní program: Ekonomie a hospodářská správa
Obor: Ekonomická analýza

Název tématu: **Analýza skokových cenových pohybů na trhu elektřinou na případu České republiky**

Rozsah práce: 50 s.

Rámcový obsah:

1. Liberalizace trhu s elektřinou s sebou přinesla nové způsoby obchodování, které byly doménou finančních a komoditních trhů. A tak se elektřina stala další běžně obchodovatelnou komoditou. Avšak oproti ostatním komoditám má obchodování s elektřinou svá určitá specifika, které způsobuje faktická neskladovatelnost elektřiny. Tato specifika mají konsekvence pro vývoj promptní ceny elektřiny, který se vyznačuje skokovými cenovými pohyby.
2. Cílem této diplomové práce bude zjistit, které faktory způsobují skoky v ceně elektřiny, a přitom bude vycházet z modelu, který byl uplatněn v Hellström et al. (2012) pro skandinávský trh elektřinou Nord Pool. Stejně jako zmíněná studie bude i tato diplomová práce sledovat dopady procesu market-coupling, kterým skandinávský trh s elektřinou prošel na přelomu 20. a 21. století, jelikož i český trh elektřinou v posledních letech podstoupil market-coupling s trhem slovenským a později i maďarským.
3. Zvláštní důraz, kterým se bude práce odlišovat od studie Hellström et al. (2012), bude věnován dopadu výroby elektřiny z obnovitelných zdrojů na promptní cenu elektřiny, a to zejména z větrných a fotovoltaických zdrojů. Předpokládá se, že elektřina z těchto zdrojů způsobuje šoky na straně nabídky, zatímco prudké teplotní výkyvy šoky na straně poptávky.
4. Zdroje dat k práci poskytnou metrologické databáze denních teplot a denních rychlostí větru, data Energetického regulačního úřadu ČR o výrobě a spotřebě elektřiny a data cen elektřiny a market coupling (OTE, a.s.).

Seznam odborné literatury:

1. Chan, Wing H., Maheau John M. Conditional Jump Dynamics in Stock Market Returns. Journal of Business & Economic Statistics. July 2002, Vol. 20, No. 3, s. 377 – 389.
2. Hellström, Jörgen, Lundgren, Jens, Yu, Haishan. Why do Electricity Prices Jump? Empirical Evidence from the Nordic Electricity Market. Energy Economics. November 2012, Volume 34, Issue 6, s. 1774 – 1781.
3. Huisman, Ronald a Mahieu, Ronald. Regime Jumps in Electricity Prices. Energy Economics. September 2003, Volume 25, Issue 5, s. 425 – 434.
4. Meyer-Brandis, Thilo a Tankov. Multi-factor jump-diffusion models of elektricity prices. International Journal of Theoretical and Applied Finance. August 2008, Volume 11, Issue 05.
5. Seifert, Jan a Uhrig-Homburg, Marliese. Modelling jumps in electricity prices: theory and empirical evidence. Review of Derivatives Research. January 2007, Volume 10, Issue 1, s. 59-85.

Datum zadání diplomové práce: **květen 2013**

Termín odevzdání diplomové práce: **prosinec 2013**

Mgr. Aleš Vokolek
Řešitel

Ing. Aleš Rod
Vedoucí práce

prof. Ing. Robert Holman, CSc.
Vedoucí ústavu

doc. Ing. Miroslav Ševčík, CSc.
Děkan NF VŠE

Abstract

The aim of diploma thesis is to find factors which cause the power price jumps in the case of the Czech Republic and at the same time it gives special emphasis on the impact of the power generation from renewables. For this purpose two-step model is applied when the first part is presented by the GARCH-EARJI model, but this model shows as unsuitable for analysis of electricity market. Thus instead of the GARCH-EARJI output, the second step of the model uses a firm boundary for definition of a jump and these founded jumps employs as a dependent variable in the ordered probit model. According to the results a large change in German power generation from renewables increases probability of power price jump. The results also confirm the impact of Germany national holidays on the Czech power price dynamics when at first holidays cause a negative price jump and then the reverse jump follows after the end of these holidays. On contrary, the influence of temperature, market coupling with Hungary and used transmission capacity are found as insignificant regarding their impact on power price jump in case of the Czech power market.

Abstrakt

Diplomová práce má za cíl zjistit faktory, které způsobují skoky v cenách elektřiny na případě České republiky, a přitom klade zvláštní důraz na zkoumání vlivu výroby elektřiny z obnovitelných zdrojů. Za tímto účelem je použit dvoustupňový model, přičemž první část představuje model GARCH-EARJI, avšak model se ukáže jako nevhodný pro analýzu trhu s elektřinou. Tudíž namísto výstupu GARCH-EARJI modelu druhá část používá pevnou hranici pro určení skoku v časové řadě ceny elektřiny a nalezené skoky vystupují jako závislá proměnná v ordered probit modelu. Provedenou empirickou analýzou bylo zjištěno, že výrazná změna ve výrobě elektřiny z obnovitelných zdrojů zvyšuje pravděpodobnost cenového skoku. Výsledky rovněž potvrzují významný dopad německých celostátních svátků na českou cenu elektřiny, kdy nejprve svátek způsobí negativní skok a po skončení svátku následuje skok v opačném směru. Avšak nebyl prokázán vliv teploty, market couplingu s Maďarskem a využitá přeshraniční přenosová kapacita na pravděpodobnost skoku ceny elektřiny v případě českého trhu s elektřinou.

Keywords

Power price jumps, Renewables, Market-coupling, Power export

Klíčová slova

Skoky v cenách elektřiny, Obnovitelné zdroje, Market coupling, Export elektřiny

JEL Classification / JEL klasifikace

C32, C35, G12, G17

List of acronyms

CAO	Central Allocation Office
ČEPS	Czech Transmission System Operator
EARJI	Exponential Autoregressive Jump Intensity
EEX	European Energy Exchange
ERÚ	Energy Regulatory Office
ETS	Emission Trading System
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
OTE	Czech electricity and gas market operator
PXE	Power Exchange Central Europe
TSO	Transmission System Operator

Content

Introduction 1

1. Electricity as tradable commodity 4

2. Power trading in the Czech Republic 15

   2.1. Trading procedure 15

   2.2. Role of OTE 17

   2.3. Cross-border trading 19

   2.4. Renewable energy scheme 22

3. Power price theory and Model description 22

   3.1. Theory and literature overview 22

   3.2. Model description 25

      3.2.1. First step 25

      3.2.2. Second step 30

4. Empirical results 34

Summary 40

Bibliography 44

Appendix 46

Introduction

The year 2000 was a key moment for the energy industry in the Czech Republic, since in that year the Energy Act (No. 458/2000 Sb.) became effective and at the same time the process of liberalization of market with energy commodities[1] started. The Act has enabled Third Part Access (TPA) which means an entity fulfilling certain conditions has right to access an energy network. In case of power market the whole process of liberalization was finished in 2006 when all customers gained the right to choose their own supplier of electricity.

From that point the electricity market[2] became fully liberalized and electricity is traded as any other commodity[3] as well as electricity market accepted principles and methods of financial market with all sorts of subjects taking part in the whole process of trading.[4] However electricity is distinguished by several features which makes electricity trading unique and dissimilar to trading with other commodities. One part of this study will look into these unique features and it will explain how these differences influence electricity price.

Like other commodities electricity price experiences volatility and sometimes price volatility is so high that we call the large price change a price jump. **The aim of this study is to find factors which cause these non-regular price moves**. For this purpose a two-step process will be performed: in the first step a model by Hellström et al. (2012) will be used, the model is called the GARCH-EARJI and it was originally developed by Chan and Maheu (2002) to reveal jumps on the stock market. Hellström et al. (2012) applied the model on the power market in Scandinavian countries. Subsequently in the second step the revealed jumps will serve as a dependent variable in an ordered probit model whose purpose is to find the factors that cause sudden electricity price jumps.

Over the last few decades the global financial market has undertaken several trends such as globalization, consolidation of particular markets, and exchange merging. Similar trends have not avoid the electricity market. Traditional national markets are being merged into larger

[1] The liberalization did not refer to only electricity market, but it also applied to gas market and heating industry.
[2] By electricity market author means only the part of electricity industry when electricity is traded as a commodity. This is a result of unbundling process which separated the transmission and distribution of electricity from its generation. Subsequently the deregulated part of electricity price is reached by trading between electricity producers and electricity suppliers and by trading between electricity suppliers themselves.
[3] Even before electricity was traded but scope of customers was very limited at first and then this scope was gradually broadened. Yet from 2006 the price of electricity was fully deregulated.
[4] On electricity market operates subjects as exchange, brokers, clearinghouse, futures traders, spot traders, banks, regulators and so on.

international markets; the best example comes from Scandinavia where national electricity markets joined into multinational power market called Nord Pool. It was finished in 2002 when the Danish power market was fully integrated into the existing market of the rest Scandinavian countries. **Since the Czech power market undertook similar[5] process with the Slovak and the Hungarian power markets, it will be analyzed, if this integration process has some jump impact on final power price**. There are other two effects which are related to the location of the Czech Republic within the European borders. The Czech Republic is not an island in the middle of an ocean and its power network is connected to the power networks of neighboring countries, therefore the excess of power as well as the lack of electricity in big countries have consequences on the Czech power network. So events in countries like Germany and France could influence not only their spot power price but even the Czech spot power price. The second effect springs from the fact that the Czech Republic is a net exporter of electricity[6] and in the context of closeness of such a big power market as Germany is[7], the Czech power price follows the German power price.

In the European power market context there is one trend, which has significant effects on situations not only in the power industry. This trend refers to the rapid growth of power generation from renewable sources. The European policy embedded in the 2020 Climate and Energy Package set a target to reduce greenhouse gas emissions by 20% in comparison with the level of 1990 and at the same time the EU wants to achieve a share of 20 % of European power consumption to be covered by production from renewable sources. To fulfill this goal EU member countries presented various programs to financially support the power generation from renewables at the expense of traditional air-polluting power producers, especially coal-fired power producers. As a result the rapid growth of renewables, most importantly the growth of wind power and solar power producers was followed by unexpected consequences. The impact of renewables on power price is unquestionable and it will be presented further in the text. But is there any connection between power price jumps and power generation from renewables? **The assumption is such that growth of power generation from renewables on the side of supply have negative impact on price of electricity and its volatility causes power price jumps.** It is the most significant difference in comparison with the paper of

[5] The process of integration can be operated through two options: market-splitting and market-coupling, these two options will be introduced in the following text.

[6] In last three years Czech net power export oscillates around 17 TWh per year which counts approximately 21 % of power generation in the Czech Republic (Source: Yearly report on the operation of the Czech electricity power grid 2013, www.eru.cz).

[7] See Figure 1 which depicts power Import/Export of Germany and the Czech Republic as the most significant net exporter to Germany.

Hellström et al. (2012) in which power price jumps were linked only to temperature change and nuclear power production jumps. To the best knowledge of the author there was no attempt to link power price jumps to renewables.

As stated above the Czech power market is very dependent on the situation of other countries, especially on the situation of the German power market. From that reason in the second step of the model a variable representing the Czech export to Germany will be used as one of its independent variables. In combination with the fact the Czech Republic presents net exporter of electricity, **there is an assumption that a significant change in the Czech export to Germany can cause jumps in electricity price on the demand side.**

This diploma is organized as follows. Section I explains how electricity trading differs from trading with other commodities and it also focuses on factors which can influence price of electricity. Section II presents electricity trading in the Czech Republic and how this trading is embedded into electricity market in Central European complex. Section III summarizes types of jumps - power price models in combination with overview of literature and describes the two-step model and explains how the model should work. Section IV presents a discussion about model suitability of the model and it analyzes empirical results as well. The final section summarizes the results and considers options for further research.

1. Electricity as tradable commodity

In the last 20 years electricity became a tradable commodity like oil, coal, copper or wheat, but unlike the mentioned traditional commodities electricity cannot be traded worldwide, simply because you cannot transfer electricity from America to Europe in practice as you can transfer oil or wheat. The uniqueness of power as a commodity indicates that power is traded very often on specialized exchanges whose domain is an energy sector.[8] Power is characterized by several features described below, but the most significant feature, which brings about the uniqueness of power and produces essential differences in comparison with other commodities, is unstorability of power.[9]

- **Unstorability**

All commodities can be stored, at least for some limited time in case of fast-rotting agriculture commodities. This is not a case of electricity. The unstorability of electricity has an impact on price during the year. Unlike the natural gas market where the growth of the volume of the gas storages in the last decade caused decreasing spread between the gas price in the summer and the gas price in the winter, electricity cannot be produced in advance to use a seasonal price spread for own profit.

But the problem with storability does not refer only to the futures market, it has an impact on the spot market as well. “Electricity must be produced just at the moment when it is consumed … and in every moment must be generated the same amount of electricity, how much is consumed” (Kolektiv autorů, 2011: 1). Subsequently a spot power trader does not have any option how he could postpone his purchase of electricity for his customers for “better” time because his consumers need electricity immediately.[10] This necessity of buying power for own customers sometimes results in closing of trade for any price[11] and at the same time it causes high volatility.

---

[8] In Europe there are many such specialized exchanges, e.g. EEX in Germany, Nord Pool Spot in Scandinavia or in case of the Czech Republic it is PXE (Power Exchange Central Europe).

[9] In practice there is one option how to storage electricity – power can be storaged through pumped-storage plant. But for its difficulties this option has only limited impact, e.g. in 2013 Czech power sector produced 1,1 % of electricity from pumped-storage plants (Source: the Yearly report on the operation of the Czech electricity power grid 2013, www.eru.cz). Theoretically there are other options how to storage electricity but none has attached more significance in practice than pumped-storage plant.

[10] Of course, trading electricity for every day is under way during several days before the actual day of business, but the trading window is very limited and it is closing very soon after moment it has been opened.

[11] From the opposite point of view it can be applied to supply side of business. Most power plants cannot be shut down immediately, thus these power plants must produce even at the moment when the price is situated under its production costs.

- **High volatility – price jumps**

The necessity to have a balanced supply-demand position forces traders with electricity to trade all the time since the Czech electricity and gas market operator (OTE) sets the settlement price for imbalances for every hour of every day. This penalization for imbalances pushes traders to balance their own position otherwise they pay a high price for every MWh of own imbalance to OTE. This dissimilar way of trading leads to large price moves and high volatility. "It is not unusual to observe annualized volatilities of more than 1000% on hourly spot prices" (Bierbaruer et al. 2007: 3464). So high volatilities are almost incomparable to the volatilities of stocks or other commodities. There are computed annualized historical volatilities for selected stocks from energy sector and energy commodities (the data are on daily basis for year 2013 and in case of commodities, the data are without weekends which would increase the volatility even more): Unipetrol 10,61 %, ČEZ 24,7 % (the price is very dependent on the futures price of electricity), natural gas spot on EEX 51 %, spot power price on PXE 513 %.

Such high volatility of power price is connected to an observance of extreme values which are called spikes or jumps.[12] Other commodities and stocks also undergo jumps, but "jumps in electricity prices are characterized by their short existence; prices fall back to a normal level sometimes after even one day" (Huisman. 2003: 426). It means that a jump is usually followed by another jump which has reverse direction to get the price to its former level.[13] The causes of the price jumps can be simplified by dividing them into two groups – on the supply side and on the demand side. In the literature the supply side causes of jumps are almost exclusively connected to failures in the power grid or to outages of the important power plants, especially to the outages of the nuclear power plants.[14] They sometimes try to find out how close the demand to the capacity constraints given by available capacity in some country is. Bogert and Dupont (2007) use the ratio of demand and available capacity as one of their two explanatory variables for the forecasting of the probability of a spike. However the Czech Republic case is somehow different, a country which exports 21 % of its production can hardly get close to its capacity constraint. The issue of price jumps and its explanatory variables will be more discussed in the following text.

[12] In Bierbauer at al. (2007) make a difference between price jumps and spikes, price jumps is characterized by sudden outages or failures in the power grid and that cannot be modelled. On contrary they interpret spikes "as a result of a sudden increase in demand and when demand reaches the limit of available capacity" and these spikes can be modelled. In other literature make no such a difference between jumps and spikes. In this study price jumps and spikes will be also perceived as synonyms.

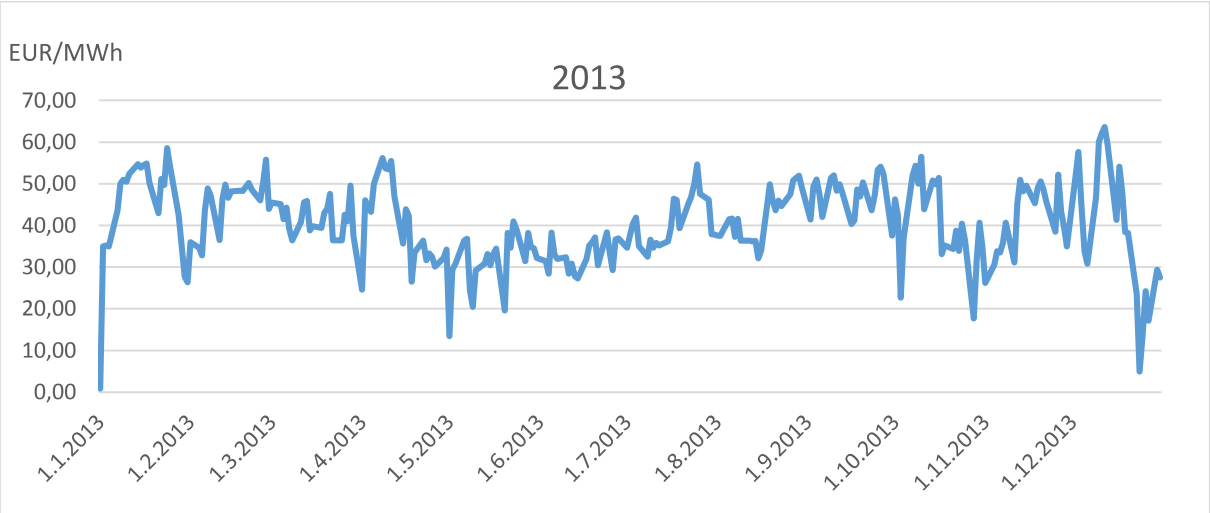
[13] In Huisman and Mahieu (2003) recognize "the process of how the electricity price reverts back to the normal regime after the spike has occurred" as last regime of their three-regime jump model.

[14] Hellström et al. (2012) choose the outages of the nuclear power plants as the independent variable representing a supply shock in the second stage of their model.

- **Seasonality**

As indicated in the previous text the price of electricity is subjected to the annual fluctuation; as most of all consumption of electricity varies during the year. For the central European area there was a typical high power consumption during the winter months while in the summer months, power consumption tended to be lower and this subsequently effected the power price.[15] Nowadays this rule cannot be completely applied as you can see in Figures 1 – 3, which depicts the Czech spot power price for years 2011 – 2013 without weekend prices data. In 2011 there is obviously a lower price in the summer whereas for the rest of the year a clear trend is somehow missing. The year 2012 experienced quite a balanced power price with the exception of an evident spike in February lasting several days. The year 2013 presents the most pronounced factor of seasonality when winter was abnormally long and March experienced untypical cold cast. The low summer price run was only interrupted at the end of July when there was the hottest period of the year and daily average temperature achieved 27 Celsius degrees. Now we get to the interesting point in a trend of power consumption.

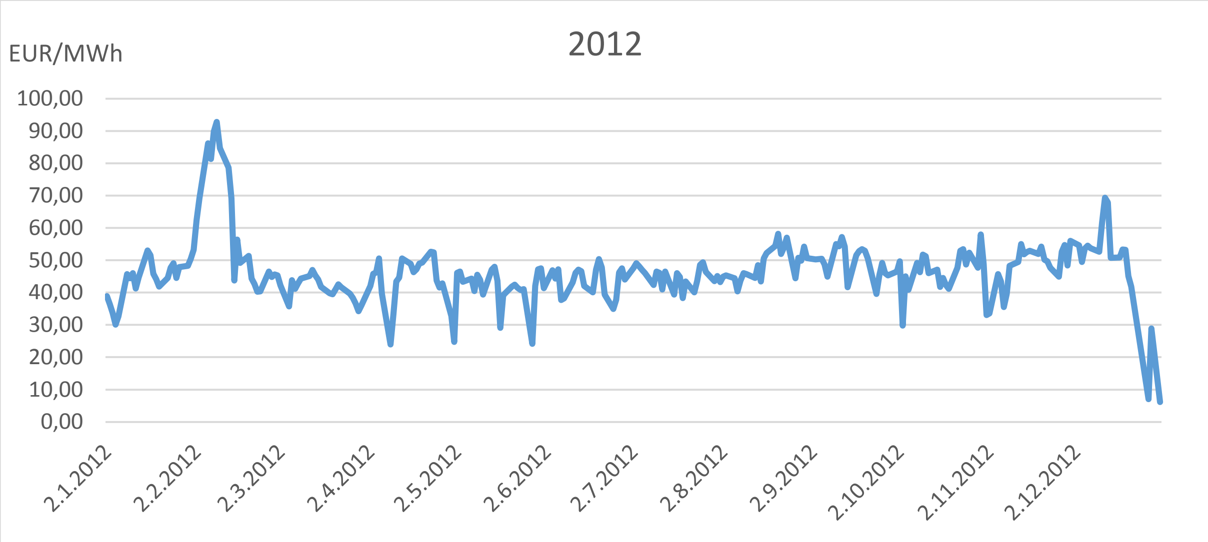
Figure 1: Spot power price 2013 – Czech Republic (no weekend prices)



source: www.ote-cr.cz

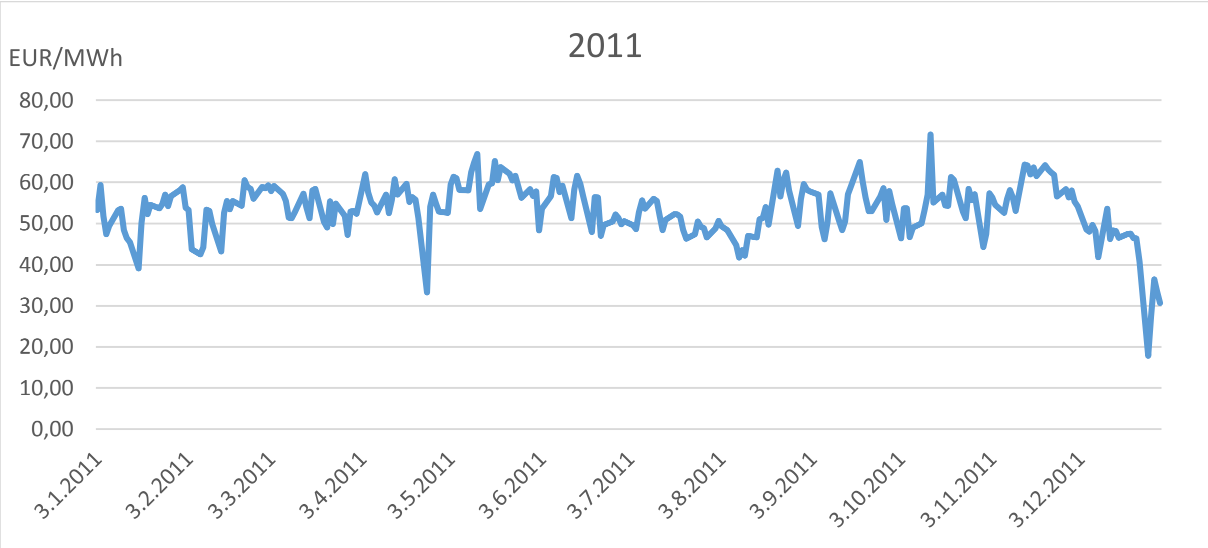
[15] In other parts of the world there are different seasonal regimes, for example in very warm and developed locations there is a high consumption in the summer because of higher usage of air-conditioning and in winter they do not need electricity for heating.

Figure 2: Spot power price 2012 – Czech Republic (no weekend prices)



Source: www.ote-cr.cz

Figure 3: Spot power price 2011 – Czech Republic (no weekend prices)



Source: www.ote-cr.cz

Originally, warm temperature and the vacation period during the summer were decreasing the power consumption, but in recent years the growth of air-conditioning increases the consumption during very hot days, thus in these days the consumption and price can rise. In Table 1 data about net power generation[16] and net power consumption[17] can be found. The

[16] Net power generation equals to gross power generation minus consumption of electricity for own generation.

[17] Net power consumption equals to gross power consumption minus new storage through pumped-storage plant, minus natural loss of power grid and minus consumption of electricity for own generation. Net power generation has to be equal to net power consumption and power export/import.

seasonality of consumption is obvious. The July consumption presents 75 % of the January consumption, however the optimizing power generators adapt to lower consumption and also decrease their own production not to allow pricing decrease too low, since some producers would not be profitable.

Table 1: Power generation and consumption 2011 – 2013 – Czech Republic

Netto		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Generation	2013	7 632	6 841	7 565	6 617	6 459	5 922	6 172	6 103	5 810	7 195	7 414	7 130
Consumption		5 697	5 141	5 518	4 803	4 580	4 327	4 281	4 369	4 527	4 969	5 202	5 242
Generation	2012	7 914	7 258	7 564	7 087	6 426	6 118	6 335	5 836	5 965	6 665	6 829	7 092
Consumption		5 568	5 696	5 248	4 747	4 527	4 376	4 297	4 382	4 420	5 028	5 190	5 319
Generation	2011	7 777	7 030	7 304	6 415	6 562	5 976	5 687	6 124	6 054	7 196	7 379	7 524
Consumption		5 707	5 270	5 379	4 638	4 666	4 393	4 264	4 446	4 384	4 926	5 291	5 270

Source: www.eru.cz

The seasonality does not have to refer only to the demand side of power market. "In some countries the supply side also shows seasonal variations in output. Hydro units, for example, are heavily dependent on precipitation and snow melting, which varies from season to season" (Bierbrauer et al. 2007: 3464). In the central European area this is the case of Switzerland most of all, when local hydro power plants have the highest production during the summer months as snow in the Alps melts, consequently Switzerland belongs to significant exporters to Germany.[18] Power from hydro generators has even one more consequence. This power is very cheap since variable cost are minimal and construction cost present sunk cost. As a result high hydro power generation could decrease the price how is implied by merit order of power generation.[19]

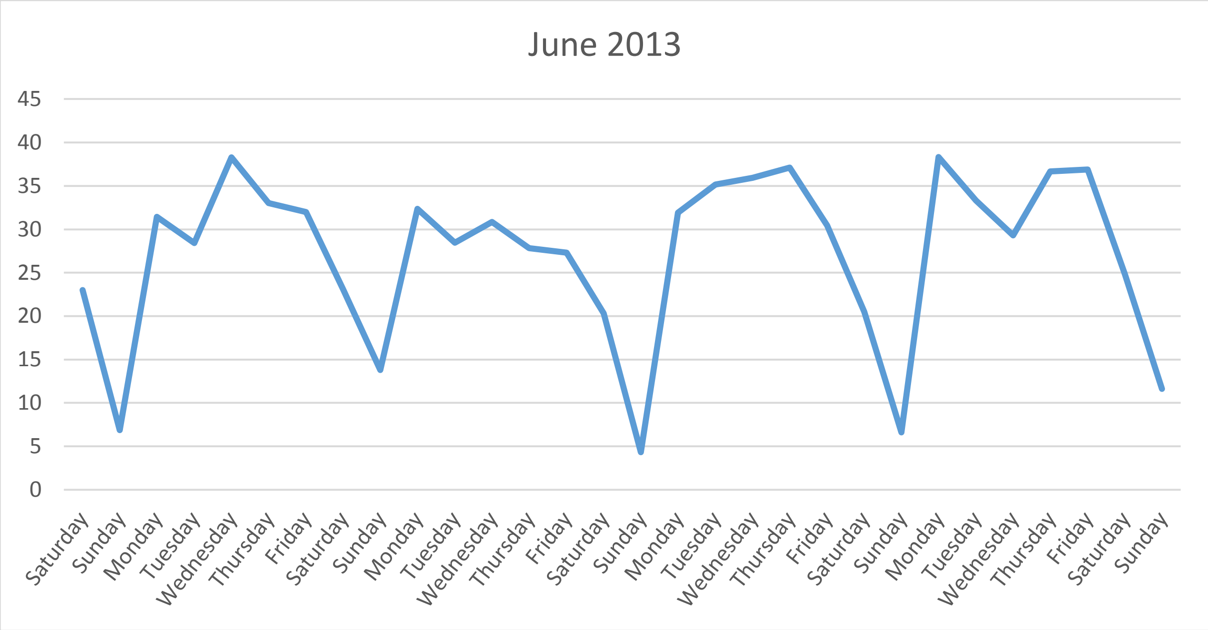
- **Day-of-week dependence**

The price of electricity is not only dependent on time during the year but also on a day during the week. In Figure 6 there is a typical pattern of power price behavior during the week: the lowest price always belongs to Sunday, Saturday is situated somewhere between labor week high price and Sunday price. This pattern is caused by work cycle during week as industries reduce or even halt its manufacturing, state authorities and schools do not work at weekends. On the other side people spend more time at home and consumption of household rises at weekends but this effect is not sufficient for compensation of the fall in industries consumption.

[18] See Figure 4.
[19] See Figure 5.

For that reason the weekend data were excluded from the study´s dataset since between Sunday and Monday there is almost always a jump; it is not need to do research to prove that.

Figure 6: Czech Power Price – June 2013



Source: www.ote-cr.cz

- **Mean reversion**

Mean reversion was already mentioned in connection with the reverse jump which follows after the first jump. The power price has some long term level which reflects the arrangement of the demand as well as structure of the power producing sector. When the power price deviates from this long term level for whatever reason, there is a market force which pushes the price back. "When there is an increase in demand, generation assets with higher marginal costs[20] will enter the market on the supply side, pushing prices higher. When demand returns to normal levels, these generations' assets with relatively high marginal costs will be turned off and price will fall" (Bierbauer et al. 2007: 3465). The causes of deviations of the demand from its standard level can spring from many reasons like a change of weather, a bank holiday or some significant event. After the cause for deviation passes, there is no reason for the price not to return to its former level. Once the cause of the price deviation was coming from only the demand side since power generators were adapting to change of the demand. Nowadays, after the growth of power generation from renewables, the cause of price deviation

[20] The order of power generators in Germany in accordance with its marginal costs is depicted in Figure 5 in Appendix.

can also spring from the supply side because significant change in power generation from renewables moves the supply curve in merit order to the right as well as it decreases market marginal costs that are marginal costs of the last power producer who is still profitable. After the power generators from renewables return to its "normal" level, power price also returns back to its mean. This comes from uniqueness of electricity, the power market cannot be oversupplied, and the excess producers must turn off their generation, the situation which happens very slowly on the other markets, on the power market this process must pass immediately.

The mean reverting feature of electricity differs from most other financial markets and this could be, beside other things, connected with lower presence of psychology than on the ordinary stock market. It cannot be said that the power market is without presence of psychology, traders are still human beings and they are leaded by emotions too. But contrary to the stock market, the power market is operated only by professionals. The stock market can deviate from its fair price for a long time, however it should not be the case of the power market; the price should soon revert back. In sum, every electricity price model must incorporate the mean reversion feature by involving the last day price.

- **Cross-border trading**

In accordance with the fact that power grids were constructed within national borders, the cross-border trading is a special chapter of the power market. In respect to the European countries, power grids were built within national borders, among these power grids were not constructed sufficient links to meet current demand, which results from the open market in the EU and price spread between individual power markets. The limited power capacity between the national power grids are called congestion[21] and this is the reason for not-single power price within the EU borders. Basically the problem of unsufficient capacity can be solved through two market solutions[22] – the explicit auction and the model of implicit auction which can acquire two forms.

In the explicit auction "market participants ask for specific amount of the transmission capacity in an open auction in return for auction price. Subsequently the capacity is assigned in order given by an offered price until all offers are satisfied or all available capacity is depleted"

[21] The congestions do not need to be established only between national markets but within national markets too. From historical reasons the congestions are taken place between the north and south of Germany or within Italy. The unsufficient transmission capacity within Germany results in a need to transfer power between south and north through the Czech Republic and Poland.
[22] Or by building sufficient links between individual power grids, of course.

(Kolektiv autorů. 2011: 104). "In Europe the explicit auctions are mostly organized on the basis of so called marginal price. The marginal price is set by last accepted offer and then this price is paid by all market participants who succeeded in the auction … if all offers are satisfied, the auction price equals to zero" (Kolektiv autorů. 2011: 105). The Czech Republic carries on this type of auction with transmission capacity to both German power grids neighboring the Czech power grid[23], Poland and Austria. In exception of special case of satisfying of all offers there has to stay some price spread between two individual areas.

The implicit auction is not an auction in the real sense of word since there is no auction where a market participant would ask for transmission capacity and would offer some auction price. The idea of implicit auction is based on a principle that "unexercised offered volume of power on market A can be paired with bid volume of power on market B, or reversely. In the ideal case it is possible to get a complete interconnection of both market areas" (Kolektiv autorů. 2011: 106). This ideal case does not have to be something extraordinary. To achieve this state there is a need for sufficient transmission capacity between the market areas. The market participants do not need to buy the transmission capacity anymore, therefore when the complete interconnection comes into force, there are no transmission costs for market participants and both market areas get the single power price. The all bid-ask pairing is managed by power exchange and mostly it is used for day-ahead market. As mentioned, two possible forms of the implicit auction exist – the market splitting and the market coupling.

The market splitting was established among the Scandinavian countries and the most distinct feature of this form is the fact that all business is managed by one exchange.[24] "This exchange accepts all offers and bids from all market participants regardless of their geographic location. At first the evaluation of offers and bids is done regardless of transmission limitation. If this evaluation meets all transmission limits – the markets stays interconnected with a single price … if not, the power exchange is forced to invalidate some tentatively paired transactions. In this case it comes to market splitting with two different prices" (Kolektiv autorů. 2011: 107).

On contrary to the market splitting form, the market coupling is managed by national power exchanges whose number is based on number of countries participating in a common market. All market participants deal only with their own national power exchange and subsequently these exchanges deal with themselves. "Every exchange evaluates own area

[23] In sum in Germany there are four owners of power grid – 50Hertz, Amprion, TenneT and EnBW. Only 50Hertz and TenneT neighbors the Czech Transmission System Operator (ČEPS).

[24] In case of Scandinavian countries it is several times mentioned Nord Pool Spot, the first international power exchange in the world.

separately … afterwards the exchanges switch calculations and try to pair the excess supply in one area with the excess demand in second area through an arranged mechanism" (Kolektiv autorů. 2011: 108). If they are not able to completely interconnect both markets with single demand curve and single supply curve, markets are decoupled with different prices. The Czech Republic created the market-coupling area with Slovakia in 2009, Hungary joined the project in September 2012 and Romania should join in November 2014 while Poland refused to join during the negotiation. The impact of this process will be studied in the empirical part of this diploma thesis.

- **Government intervention versus deregulation**

In the European power sector two processes have been under way during the last decade – growing government interventions and deregulation process– two contradictory processes at first sight. Nowadays the EU authorities create important policies influencing the Czech power sector, the deregulation process emerges from the EU energy packages, until now three energy packages were adopted. At first the deregulation process referred to the separation (at least legally) of transmission system operator (TSO) from traditionally national power producers, this process is called the unbundling. The unbundling is connected with the TPA and the opening power market for all customers, firstly for companies and in 2006 for households. After the unbundling and the TPA were adopted, the trading with power could start and number of the power trading companies started to grow.

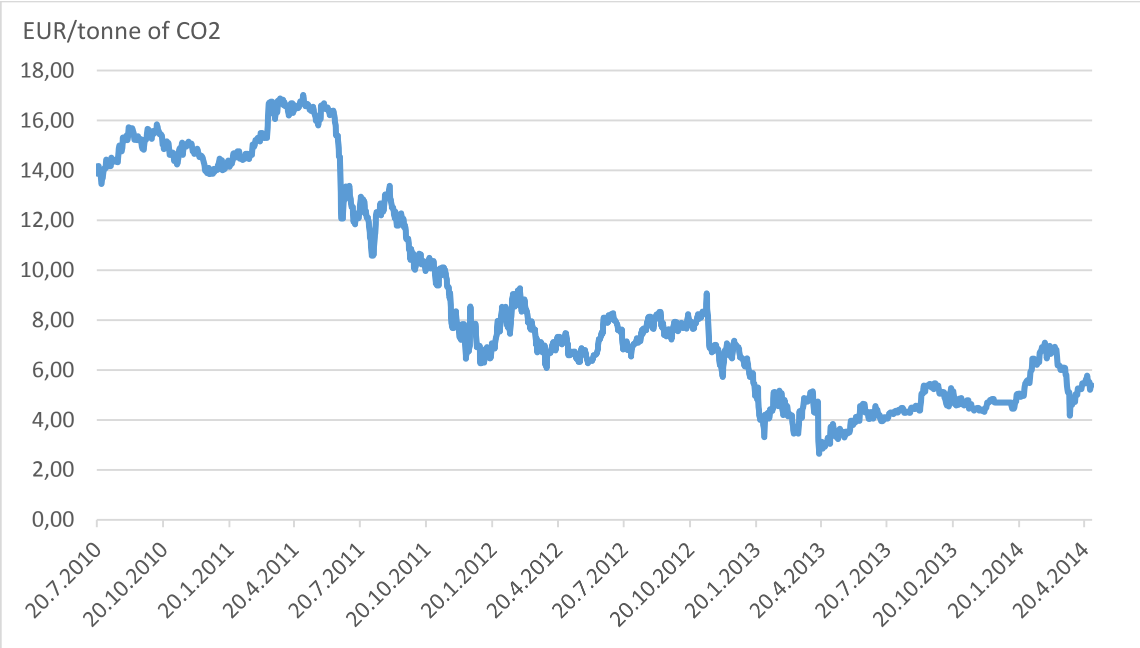
The important aspect of the government intervention appeared in 2005 when the EU initiated the Emission Trading System (ETS) which got into full operation in 2007. The ETS presents a scheme for trading with CO2 emission allowances, this system should disadvantage power generation from the air-polluting power plants such as coal and lignite power plants.[25] The system of emission allowances should rise the power generation cost of the air-polluting power plants, since the utilities must pay for every released tonne of CO2 into air during its power generation. As a result the system should promote low-carbon power generation such as natural gas power plants or the power generation from renewables.[26] How the emission

[25] The emission trading does not refer to the only power sector but also to energy-intensive and air-polluting industry sectors such as oil refineries, steel works, metal a glass industries, etc.

[26] The support of the power generation from the nuclear plants is questionable because of the current policy of some members of EU which are planning to shut down own nuclear plants or they are asking for closing of the nuclear plants in other countries. The system could support a construction of the new nuclear plants in case of a stable high price of the emission allowances since the construction of the nuclear plant is a long-run project. The current uncertainty about development of price of the emission allowances cannot contribute to pro decision of the nuclear plant.

allowances system influences the power market can be seen in Figure 5 which depicts the impact of the payment for a released tonne of CO2 on German merit order. The emission allowance system increases the marginal price in the power market and on the first sight the Figure assumes a high price for the emission allowances. Figure 7 displays development of price of the EU emission allowances in last four years. There is an obvious fall in the emission price starting in the middle of 2011 and ending in the middle of 2013 when the EU authorities launched a negotiation about so-called back-loading plan which should result in withdrawal of hundreds millions of the emission allowances.

Figure 7: EU Emission Allowances price

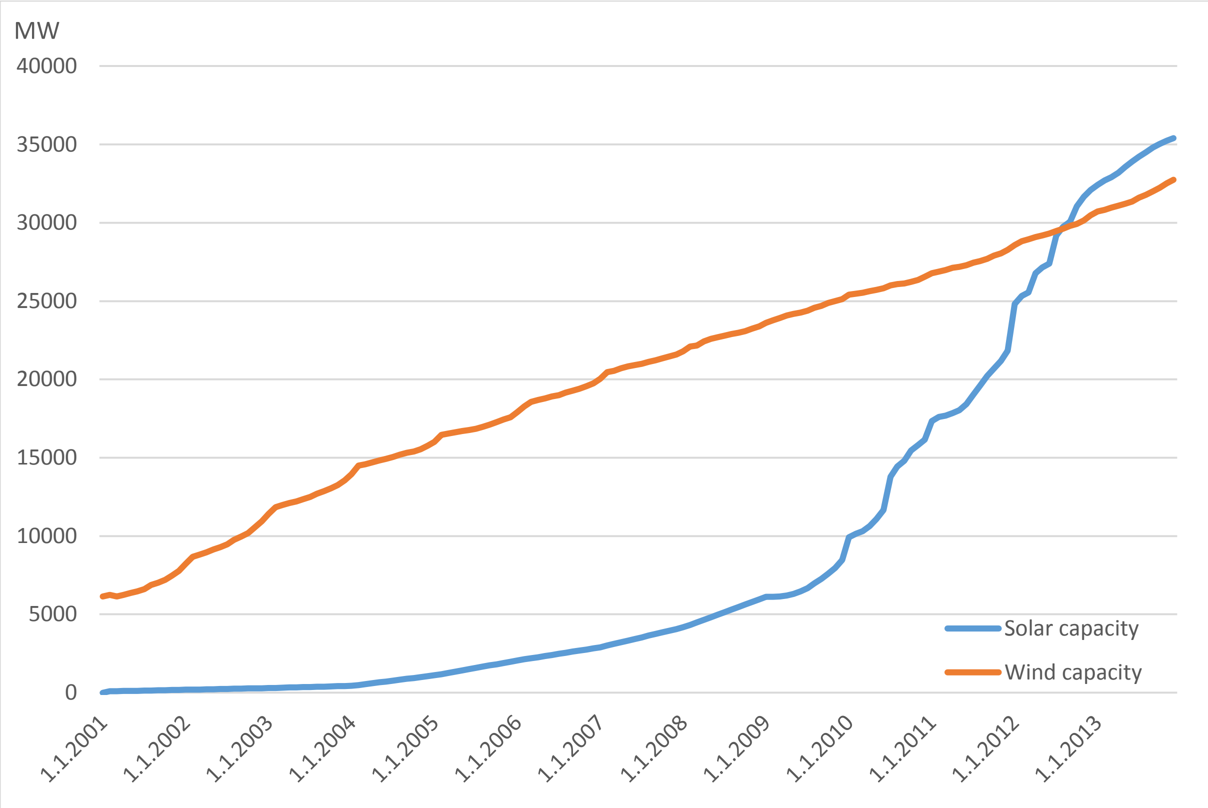


Source: www.eex.com

The Third Energy Package relates to the target to cut greenhouse gas emissions by 20 % in comparison with the level in 1990 and the target to achieve a share of 20 % of the European power consumption to be covered by renewable energy. The later target brings out far-reaching consequences for the whole energy sector. The financial support in the form of long-term priority dispatch in combination with premium prices reflecting the investment costs, called feed-in tariff[27], caused the extensive growth of the share of renewable energy in power generation mix of many European countries. Figures 8 and 9 show the development of solar and wind power generation capacity in Germany, and solar power generation capacity in the Czech Republic, respectively.

[27] There are other options how to support the development of renewable energy, such as the green premiums, but the feed-in tariff support is the most widespread.

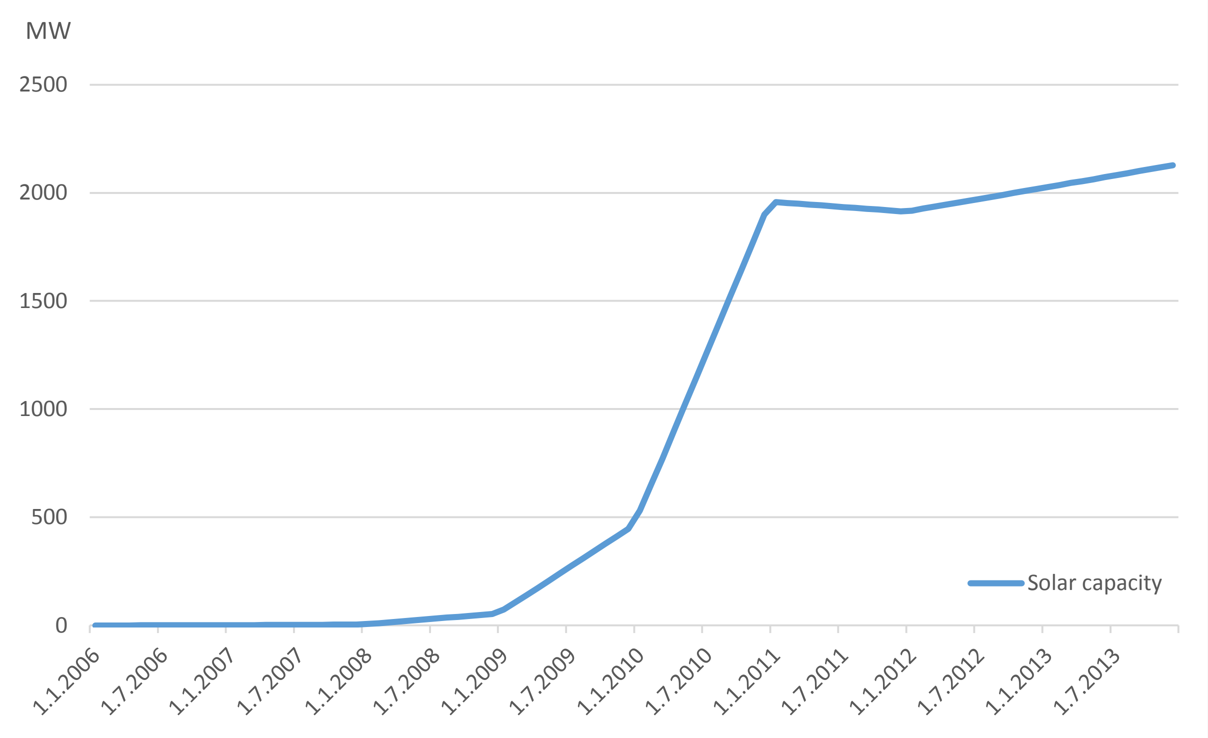
Figure 8: Development of solar and wind capacity - Germany



Source: Thomson Reuters

While the wind power capacity grows by almost perfect linear trend, the solar power capacity grows exponentially at least in Germany although it looks like that the trend is slowing in the last two years. In case of the Czech Republic the development of solar power resembles logistic curve since the financial support of new photovoltaic power stations was significantly reduced and the growth has almost stopped. “Already 25 percent of German energy comes from renewable resources” (NY Times) at the start of 2014, such a rapid expansion is doing trouble to utilities, which were not prepared for such a dynamic change of their market. A the marginal price decreases, the surplus of supplier also decreases, thus many power plants owned by the traditional utilities either have had smaller margin or even have become unprofitable.

Figure 9: Development of solar capacity – Czech Republic



Source: Thomson Reuters

2. Power trading in the Czech Republic

This chapter presents power trading in the Czech Republic and how the Czech power market is set in the framework of the central European market, especially the Czech connection with Germany. To the best knowledge of the author, the Czech power trading is not unique in any way and it fully reflects the EU energy policy although there are some differences among the member countries (see the text below).

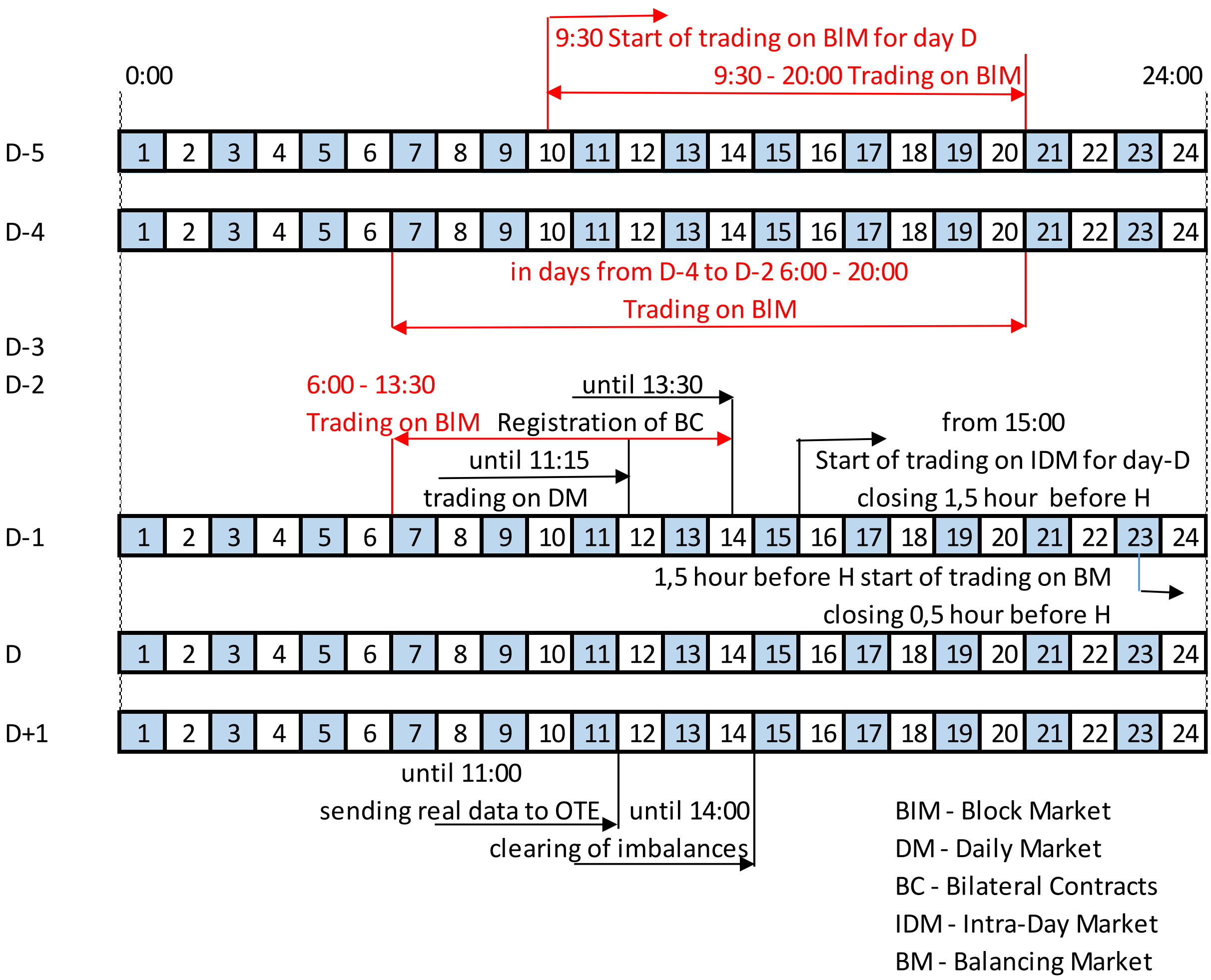
2.1. Trading procedure

As was said in the previous text, electricity must be consumed just at the moment when it is produced but this fact does not prevent from buying this electricity in advance. In fact, electricity has to be bought in advance in order to the transmission system dispatching control would be able to operate power grid. Moreover electricity must be bought in advance for one another reason. The power producing companies sell part of its future production to hedge own price because they have to also buy lignite, coal, gas or uranium in advance in long-term contracts while power companies without own power generation or with limited own power generation have to hedge its position since they need to cover contracts with their customers. But this hedging refers to the futures market, on the spot market they have to balance their position by buying additional power or by selling excess power. And there arises the necessity which relates to the uniqueness of power trading and resulting special features of electricity.

Basically in the Czech Republic power market can be divided into two types – organized market managed by power exchange and unorganized market operated by brokers. The later type is very large in respect to its options and more importantly there are no complete data about trading. Therefore this study works only with data from the organized market. In the Czech Republic the organized market is operated by two power exchanges – OTE and PXE.

While PXE organizes only the futures market which is not interest of this study, OTE organizes the Czech spot power market. The spot power market consists of four parts – the block, the daily, the intra-day and the balancing market. While the daily market, the intra-day and the balancing market follow after each other, the block market has very similar time schedule like the daily market. Figure 10 shows the scheme of all spot markets with their time schedule.

Figure 10: The scheme of the Czech power market



Source: Cheminišec, 2010

On the Block market blocks of electricity are traded, among the most significant belong Base (0-24), Peak (8-20) and Off-peak (0-8,20-24).[28] On the daily market individual hours of all day are traded thus the whole daily market splits into 24 markets. The daily market must be closed until 11:15 before day of delivery, thus it is sometimes called the day-ahead market. After the end of the day-ahead market the intra-day market follows, which has to be always closed 1,5 hour before delivery hour. Finally, the balancing market runs only 1 hour for each daily hour, starts 1,5 hour before and ends 0,5 hour before hour of delivery. The balancing market differs from the other spot markets in one way – ČEPS always stands on one side of the trade because it needs to balance the power grid according to current situation. The balancing market ends 0,5 hour before delivery hour because ČEPS needs time to be able to activate regulation energy which reduces size of imbalances.

2.2. Role of OTE

The Czech spot power market is operated by OTE, which organizes trading between power companies and at the same time it facilitates this trading since it requires a financial deposit of trading companies and controls if this deposit is sufficiently high in respect to the company's volume of trades. Next it counts the final auction price for the day-ahead market, and one day after the day of delivery when it receives real and estimated[29] data from distribution companies, OTE makes clearing of imbalances of every trading subject of settlement[30] and manages settlement of these imbalances. Finally, OTE manages a transfer of customers between the individual power companies.

This study focuses on the daily market price therefore it is necessary to show how the final day-ahead price is achieved. The smallest trade amount is 1 MWh and it can be bought amount of MWh with one decimal point, the all Czech power market is trading in euros. The market price for 1 MWh of certain hour is achieved through the auction, OTE organizes this auction when it accepts bids and offers for this hour on certain amount of MWh for certain price.

---

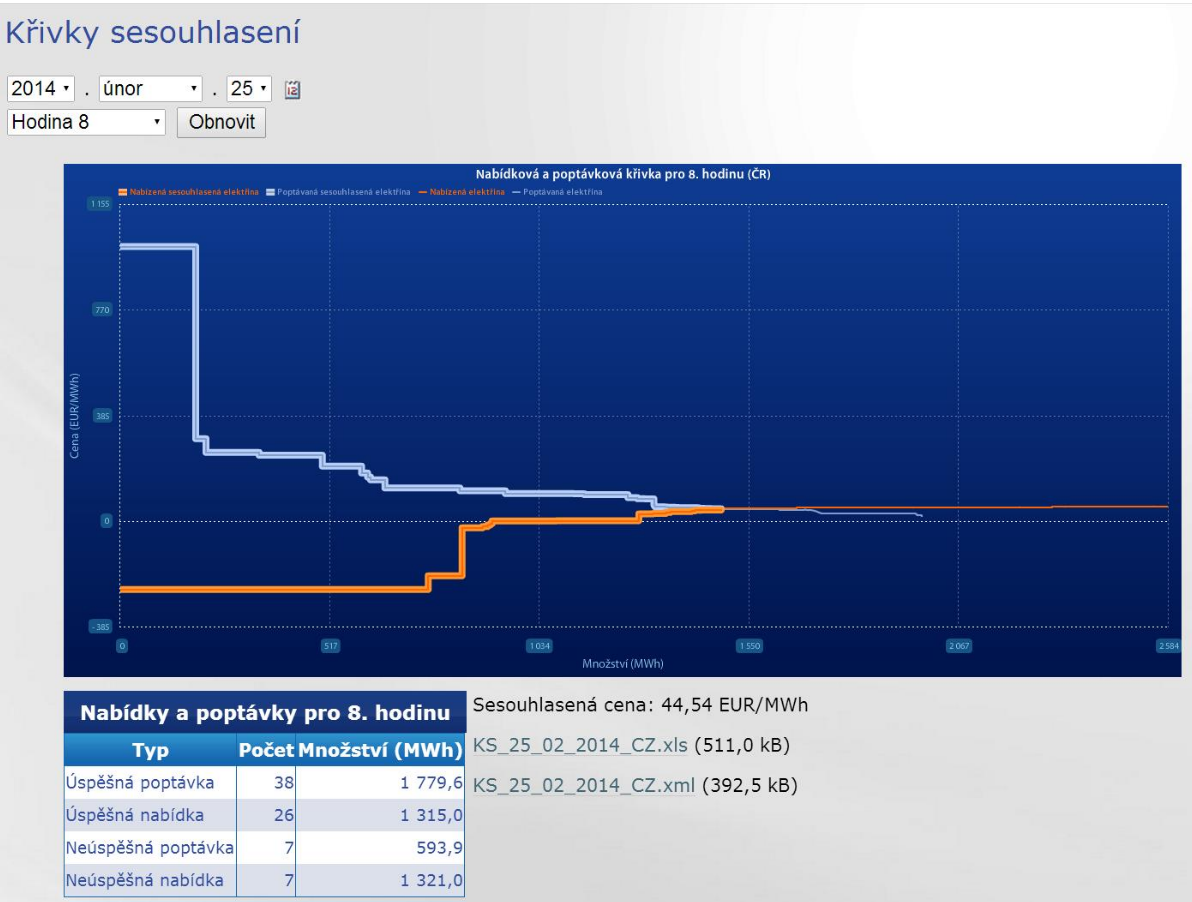
[28] In parentheses there are hours which are bought by purchase of the block.

[29] Only some companies have online measuring which enables to gain data immediately, consumption of other subjects has to be estimated.

[30] Imbalances are counted only for subjects of settlement since these subjects assume financial responsibility for imbalances from other subjects of the power market called as the market participants. For example a producer from photovoltaic system is the market participant but it rather to cede its responsibility for imbalances to another subject since it would have to care about how much power it generates and when it generates power.

Figure 11 shows the example of such auction, specifically it refers to the auction for 8th hour on the 25th February 2014. Figure 11 depicts the supply and demand curve for this hour, and successful bids and offers are highlighted by bold style and they create so-called matching curves. The difficulties with matching of bids and offers come from the fact that the supply and demand curves are discontinuous therefore their intersection does not have to be perfect in one point and they can overlap only partly, OTE solves this difficulty by its auction rules. The settlement price was 44,54 EUR for MWh, this price is called the marginal price and all successful bidders pay this price and all successful sellers receive this price thus no matter what price you bid or offer you always get the price as everyone else in case you are in successful part of the supply curve, or demand curve, respectively. This way, how the settlement price is achieved, can lead to tactics to offer power for very low price or bid for very high price to be sure of making the settlement. This is the reason why there are several offers with a negative price.[31]

Figure 11: OTE - Matching curves of 8th hour on the 25th February 2014



Typ	Počet	Množství (MWh)
Úspěšná poptávka	38	1 779,6
Úspěšná nabídka	26	1 315,0
Neúspěšná poptávka	7	593,9
Neúspěšná nabídka	7	1 321,0

Source: www.ote-cr.cz

[31] This does not mean that the auction cannot result in a negative price, because it is not the unusual result. But for price of the Base product (which is in the interest of this study) it is still rare in the Czech Republic, it happened only during Christmas holidays 2012.

You can notice more interesting fact that successful bid amounts to 1 779,6 MWh while the successful offer amounts to 1 315 MWh, this inequality will be explained in the next part of the thesis. The unsuccessful bidders and sellers can make a settlement in the following intra-day market or they can sell power to ČEPS in the balancing market, or buy power from ČEPS, respectively. But it is a very risky position since the traders cannot be sure whether ČEPS will buy or sell power, moreover whether ČEPS will make a settlement with them. If ČEPS does not make a settlement with such a trader, he will increase his volume of imbalances. In the following day OTE counts volume of imbalances for the subject of settlement representing by his trader, and the subject of settlement will pay for its imbalances or it get will get paid for its imbalances[32], it depends on the system imbalance.[33]

2.3. Cross-border trading

In the Czech Republic the cross-border trade with power runs by two options – through explicit auction between ČEPS and the German power grids (50Hertz, TenneT), ČEPS and the Austrian power grid (APG), ČEPS and the Polish power grid (PSE), and through implicit auction between ČEPS and the Slovakian power grid (SEPS) since the Czech and the Slovakian power market keep market coupling.

In case of the market coupling between the Czech Republic and Slovakia there is not a futures market for the transmission capacity between them. Therefore all the transmission capacity is being allocated through the spot market, at first through implicit auction of the day-ahead market which was explained in the previous text. The unused transmission capacity from the day-ahead market can be allocated through the intra-day auction of transmission capacity organized by ČEPS. If day-ahead markets are decoupled, ČEPS organizes so-called shadow auction for the profile ČEPS – SEPS[34] according to which is transmission capacity allocated.

Figure 12 shows results of market coupling between the Czech, Slovakian and Hungarian day-ahead market again on the 25th February 2014. The markets are almost fully coupled with the only one exception – 19th hour when Hungarian market decoupled and this hour costs 62,57 EUR/MWh in Hungary. The perfect coupling between these markets is not matter-of-course since the Hungarian day-ahead market often decouples from the remaining

---

[32] To the knowledge of author it belongs to unique feature of the Czech power market, in other markets it is not possible to get paid for its imbalances.

[33] The system imbalance is sum of imbalances of all subjects of settlement. When in sum there was lack of electricity in the power grid and the subject of settlement had excess of electricity, he gets paid for his imbalance because he helped to grid, or reversely.

[34] ČEPS organizes shadow auction every day, but it comes to work only in the case of decoupling. More about the shadow auction can be found on www.ceps.cz.

two markets and Slovakia and the Czech Republic sometimes decouples too. To finish the explanation of the previous part look at 8th hour of the profile SR-ČR, the transferred amount from the Slovakian power grid to the Czech power grid equals to 464,6 MWh, which is the exact amount which was missing in the successful sells to match the successful bids. Thus the transfer of power lowered Czech price for 8th hour and at the same time it satisfied part of demand. The rest of transmission capacity (1786,4 MW) could be allocated in the intra-day auction for 8th hour of 25th February 2014. This transfer is a nice illustration that research of the Czech power market price cannot focus only on determinants within Czech borders.

Figure 12: Results of market coupling of the Czech, Slovakian and Hungarian power market on the 25th February 2014

Výsledky denního trhu ČR-SR-HU - 25.02.2014											
Hodina	Cena ČR (EUR/MWH)	Cena SR (EUR/MWH)	Cena HU (EUR/MWH)	Přeshraniční tok (MWh)				Dostupná přenosová kapacita (MW)			
				ČR→SR	SR→ČR	SR→HU	HU→SR	ČR→SR	SR→ČR	SR→HU	HU→SR
1	23,00	23,00	23,00	0,0	1 245,6	0,0	855,2	769,0	2 231,0	414,0	1 486,0
2	23,01	23,01	23,01	0,0	1 549,5	0,0	1 071,8	748,0	2 252,0	415,0	1 485,0
3	21,00	21,00	21,00	0,0	1 607,9	0,0	1 149,7	787,0	2 213,0	415,0	1 485,0
4	20,00	20,00	20,00	0,0	1 662,1	0,0	1 187,2	793,0	2 207,0	414,0	1 486,0
5	22,08	22,08	22,08	0,0	1 631,2	0,0	1 172,5	742,0	2 258,0	415,0	1 485,0
6	24,12	24,12	24,12	0,0	1 105,1	0,0	805,5	806,0	2 194,0	414,0	1 486,0
7	35,00	35,00	35,00	0,0	839,2	0,0	509,6	766,0	2 234,0	414,0	1 486,0
8	44,54	44,54	44,54	0,0	464,6	91,4	0,0	749,0	2 251,0	413,0	1 487,0
9	47,10	47,10	47,10	0,0	197,5	252,6	0,0	789,0	2 211,0	413,0	1 487,0
10	36,80	36,80	36,80	0,0	202,4	78,5	0,0	653,0	2 347,0	413,0	1 487,0
11	32,12	32,12	32,12	0,0	44,9	268,3	0,0	654,0	2 346,0	413,0	1 487,0
12	31,02	31,02	31,02	39,9	0,0	314,0	0,0	664,0	2 336,0	413,0	1 487,0
13	30,00	30,00	30,00	0,0	5,3	289,8	0,0	665,0	2 335,0	413,0	1 487,0
14	30,37	30,37	30,37	20,3	0,0	311,1	0,0	660,0	2 340,0	414,0	1 486,0
15	31,50	31,50	31,50	30,3	0,0	330,0	0,0	656,0	2 344,0	414,0	1 486,0
16	33,80	33,80	33,80	0,0	108,7	139,6	0,0	683,0	2 317,0	414,0	1 486,0
17	36,88	36,88	36,88	0,0	156,8	9,9	0,0	702,0	2 298,0	414,0	1 486,0
18	48,42	48,42	48,42	31,7	0,0	321,0	0,0	772,0	2 228,0	414,0	1 486,0
19	61,68	61,68	62,57	0,0	74,7	414,0	0,0	727,0	2 273,0	414,0	1 486,0
20	56,50	56,50	56,78	0,0	159,3	414,0	0,0	737,0	2 263,0	414,0	1 486,0
21	46,20	46,20	46,20	0,0	26,7	238,1	0,0	748,0	2 252,0	414,0	1 486,0
22	35,33	35,33	35,33	0,0	374,6	0,0	129,7	677,0	2 323,0	414,0	1 486,0
23	33,41	33,41	33,41	0,0	305,5	71,6	0,0	806,0	2 194,0	414,0	1 486,0
24	27,55	27,55	27,55	0,0	417,9	0,0	139,1	932,0	2 068,0	414,0	1 486,0

Source: www.ote-cr.cz

The explicit auction option with the rest of the neighboring power grids runs not only on the spot market, but also on the futures market. At first, part of transmission capacity is allocated through year and month auctions, subsequently unused capacity of this sold capacity can be sold again on the spot market[35] and in this way it expands the supply of capacity on the spot market. The year, month and day-ahead markets are organized by Central Allocation Office (CAO) which organizes transmission capacity auctions in the central European area. ČEPS again organizes the intra-day auction of remaining transmission capacity. All transmission capacity is distributed between particular auctions in advance. Table 2 shows the example of how transmission capacity for profile ČEPS - TenneT is distributed between particular auctions on the 25th February 2014 – in year and month auctions were allocated 850 MW of capacity in advance but long-term nominations[36] amounted to only around 650 MW, the nominations differed according to hour, in the day-ahead auction was allocated also around 650 MW of capacity.[37] Thus in the year, month and day-ahead auctions 1300 MW of capacity were allocated, certain amount of MW of capacity was left for the intra-day auction.[38]

Table 2:

Distribution of transmission capacity ČEPS – TenneT between particular auctions

Results of day-ahead auction ČEPS – TenneT on 25th February 2014

Long-term nominations of transmission capacity ČEPS – TenneT on 25th February 2014

Product	Source	Sink	Requested Capacity [MW]	Allocated Capacity Daily [MW]	Auction Price [EUR/MWh]	Total Companies	Awarded Companies	Allocated Capacity Yearly [MW]	Allocated Capacity Monthly [MW]	Total Allocated Capacity Y+M+D [MW]	Long Term Nominations [MW]	Allocated Capacity D + LT Nominations [MW]
H01	CEPS	TenneTDE	1 758	640	0,5	17	12	450	400	1 490	660	1 300
H02	CEPS	TenneTDE	1 783	640	0,5	17	12	450	400	1 490	660	1 300
H03	CEPS	TenneTDE	1 783	640	0,51	17	11	450	400	1 490	660	1 300
H04	CEPS	TenneTDE	1 783	640	0,51	17	11	450	400	1 490	660	1 300
H05	CEPS	TenneTDE	1 783	640	0,56	17	11	450	400	1 490	660	1 300
H06	CEPS	TenneTDE	1 783	640	0,51	17	10	450	400	1 490	660	1 300
H07	CEPS	TenneTDE	1 797	640	0,68	16	9	450	400	1 490	660	1 300
H08	CEPS	TenneTDE	1 822	640	0,76	17	12	450	400	1 490	660	1 300
H09	CEPS	TenneTDE	1 687	640	0,77	16	8	450	400	1 490	660	1 300
H10	CEPS	TenneTDE	1 548	640	0,53	16	9	450	400	1 490	660	1 300
H11	CEPS	TenneTDE	1 533	640	0,51	15	7	450	400	1 490	660	1 300
H12	CEPS	TenneTDE	1 559	655	0,51	15	8	450	400	1 505	645	1 300
H13	CEPS	TenneTDE	1 569	655	0,48	15	8	450	400	1 505	645	1 300
H14	CEPS	TenneTDE	1 569	655	0,48	15	8	450	400	1 505	645	1 300
H15	CEPS	TenneTDE	1 568	640	0,48	15	8	450	400	1 490	660	1 300
H16	CEPS	TenneTDE	1 543	640	0,25	15	10	450	400	1 490	660	1 300
H17	CEPS	TenneTDE	1 648	640	0,42	16	10	450	400	1 490	660	1 300
H18	CEPS	TenneTDE	1 697	640	0,45	16	10	450	400	1 490	660	1 300
H19	CEPS	TenneTDE	1 762	640	0,77	16	11	450	400	1 490	660	1 300
H20	CEPS	TenneTDE	1 762	640	0,78	16	7	450	400	1 490	660	1 300
H21	CEPS	TenneTDE	1 700	660	0,68	17	10	450	400	1 510	640	1 300
H22	CEPS	TenneTDE	1 674	645	0,58	16	9	450	400	1 495	655	1 300
H23	CEPS	TenneTDE	1 673	640	0,58	16	9	450	400	1 490	660	1 300
H24	CEPS	TenneTDE	1 748	640	0,75	16	11	450	400	1 490	660	1 300

Source: www.central-ao.com

[35] It can be also sold on secondary market, but this market is unorganized.
[36] The real amount which power companies having right for capacity want to use.
[37] 1300 MW – 650 MW = 650 MW for the day-ahead auction.
[38] On the 25th February 2014 in the intra-day auction 250 MW of capacity were allocated, it totals to 1550 MW of allocated capacity, but only 1240 MW were really used according to data (source: www.ceps.cz).

2.4. Renewable energy scheme

Until 2020 the Czech power sector has to cover 13 % of gross power consumption by power generation from renewables, this number was stated in appendix of the Directive 2009/28/EC on the promotion of the use of energy from renewable sources. In Figure 13 can be seen that the Czech Republic fulfilled this target already in 2013. The largest share of renewable energy production comes from biogas generation (2 241 GWh) and from photovoltaic generation (2 033 GWh)[39].

The Czech Republic has two systems of renewable energy support[40]: feed-in tariffs and green premiums whose prices are set by the ERÚ. Power producers have the right to choose one of these systems. The feed in-tariffs promise to a power producer a purchase for his production for 15 years for certain price and the purchasing party is either a transmission system operator or a distribution system operator and one of these operators assumes responsibility for imbalances.

In case of green premiums, a producer from renewables either sells power himself on organized markets or he can sell it to some subject of settlement who assumes responsibility for imbalances for power producer. A power producer from renewables gets a premium for generated power and market price for sold power from the purchaser. Cost of both systems is paid by final consumers and from the national budget.

3. Power price theory and Model description

This part of the thesis will introduce the overview of basic types of power price models and related literature. Since power price theory presents a very broad and complicated topic, particular model types will be presented only briefly. Subsequently the two-step model will be described including explanation of chosen independent variables.

3.1. Theory and literature overview

There is a whole range of approaches how to model a power price, and since a power price development is characterized by jumps, newer models also include a jump component.

[39] The source of data is the Yearly report on the operation of the Czech electricity power grid 2013.
[40] The support of new built renewable energy generators was almost ended in September 2013, from 1.1.2014 only small hydro-generators up 10 MW have unconditional support. Wind generators, geothermal generators, and energy from biomass have right for support only in case of license issued until 2nd October 2013 and putting into operation until 1st January 2015 (source: Ihned, web).

The power price models can be divided into four following groups: Fundamental models, Mean-reversion (Markov-diffusion) models, Jump-diffusion models and Regime-switching models.

Fundamental models

A fundamental model tries to achieve the modelled price reflecting variation in fundamental factors of electricity. The most common fundamental factor is the power demand which is often seen as the hinge in the power market balancing of supply and demand. The reason for that comes from the fact that demand was the volatile variable while supply was considered as deterministic – simply adapting to changing demand. With the arrival of renewables it does not hold anymore, merit order moves to the right and to the left according to the size of the power production from renewables which enjoys the feed-in support. As a result current fundamental models cannot only count on the demand, but they also need to include the changing structure of the supply.

One such a model is developed in Boogert at al. (2007) who seeks to link the spot power price with the ratio of the demand and available capacity on case of the Dutch power market. They grant relevance to renewables by including wind power into sum of available capacity at least in theory, but without wind power data they were not able include it in their final model.

Mean-reversion (Markov-diffusion) models

Another group of models proceeds only from time series of power price when it uses stochastic behavior of power price to model power price itself.[41] As a nice example of this type Lucia et al. (2002) can serve. They divide the power price development (P_t) into two parts:

$$P_t = f(t) + X_t,$$

where f(t) represents a deterministic component which reflects seasonality and the day-of-week effect and X_t represents a diffusion stochastic component. The deterministic component have many forms and options, but the stochastic part is typically represented by following general equation which is actually based on the Vasicek model:

$$dX_t = \kappa(\mu - X_t)dt + \sigma dW_t,$$ [42]

where X_t follows Ornstein-Uhlenbeck process, sometimes called mean-reverting process according to feature which forces the state variable to return to its long-term mean level (μ).[43] X_t presents the deseasonalized price because the deterministic part was removed from the price.

[41] From that reason these models are sometimes called one-factor models.

[42] The equation is slightly modified in comparison with original Lucia at al. (2002) equation since there is explicitly expressed μ and they assumed this variable to be equal to zero and missed it from their equation.

[43] This type of model is also sometimes called as Markov model because the price development depends only on current value of power price or in other words the stochastic part of price depends only on current distance from long-term level, not on past.

As said in the previous part of the study, the mean-reverting feature belongs to important characteristics of behavior of power price. κ presents speed of adjustment, how quickly the price returns back to its long-term level, while W_t represents a standard Brownian motion or the remaining stochastic behavior. "The main drawback of the model specification is its lack to explain the observed price spikes" (Bierbrauer et al. 2007: 3466).

Jump-diffusion models

This drawback is solved by jump diffusion models which adds another component – a jump component. This type of model expands the basic mean-reversion model about jumps:

$$dX_t = \kappa(\mu - X_t) + \sigma dW_t + q dJ_t,$$

and subsequently models differ by way how model the jump component J_t. The above equation belongs to the one-factor models, the two-factor model is presented in Meyer-Brandis et al. (2008) who separates the mean-reverting process and creates two different mean-reverting processes – one corresponds to normal behavior of power price and should be slower and the second one corresponds to jumps when the returning back process is assumed to be fast because the reason for jump quickly disappears.

Regime switching models

A different approach was chosen by Huisman and Mahieu (2003) who also use the fact that the power price behavior is characterized by two types of mean-reverting process. But instead of incorporating another mean-reverting process into diffusion model Huisman and Mahieu presented a model which switches between three regimes: "a normal regime (regime 0) when price follows 'normal' electricity price dynamics, an initial jump regime (regime + 1) that models the process when the price of electricity suddenly increases and decreases in case of spike and regime (regime – 1) that describes the process of how the electricity price reverts back to the normal regime after the spike has occurred" (Huisman et al. 2003: 429). This model continues in Vasicek specification, but each regime has own equation when regimes 0 and – 1 are characterized by basic Ornstein-Uhlenbeck process, and regime + 1 has average size of jump instead of the mean reverting part, all regimes have own volatility parameter. The important feature of model are probabilities of transition between regimes which are calculated through Markov transition matrices. The model takes into account the typical behavior of power price when jump is usually followed by another jump – reverse jump, but it is also its disadvantage at the same time since the model prescribes the only way how electricity price can develop. The model excludes the option that after jump can follow another with the same direction or the model prescribes the immediate reverse jump, but power price does not have to revert back immediately especially when there are more holidays together.[44]

3.2. Model description

The model employed in this thesis is divided into two parts. The first part tries to reveal jumps in power price whereas the second part models the identified jumps from the first part. The second part aims to find factors causing the power price jumps.

3.2.1. First step

The model used in this thesis is called the generalized autoregressive conditional heteroskedasticity – exponential autoregressive jump intensity (GARCH–EARJI) jump model and it presents the first step of jump modelling. Hellström et al. (2012) used this model to study the power price jumps on the Nord Pool market, but the model was originally developed by Chan and Maheu (2002) to study jumps on the stock market. After the first introduction, the model was better explained but also partly modified in Maheu and McCurdy (2004)[45].

This model differs from the above mentioned models in respect to the fact they make power price modelling while this model tries to estimate probability of jumps in power price. Therefore while the above models studied the power price as a whole, the primary focus of the GARCH–EARJI model is concentrated on revealing jumps in power price. As diffusion models the GARCH–EARJI proceeds only from power price time series[46] and it does not take into account fundamental factors on the power market.

Instead of power price P_t, the model uses the logarithmic return $r_t = \ln(P_t/P_{t-1})$ when P_t is conditional on information set $\phi_{t-1} = (r_{t-1},\ldots,r_1)$ which means that current power price reflects all available information from history which is contained in past power prices. The basic logic of the model comes from the relation:

$$r_t = \mu_t + \varepsilon_{1t} + \varepsilon_{2t}, \tag{1}$$

when power price return (r_t) is decomposed into the time-varying conditional mean of return (μ_t) and random disturbance terms which present ‘normal’ price variation (ε_{1t}) and jump variation (ε_{2t}), respectively. These random disturbance terms are sometimes called innovations and are assumed to be independent. Normal price variation

[44] In fact it happened to the Czech power price during Christmas holidays 2012 when after jump power price stayed another two days around zero than reverted back.
[45] The modification referred to only different specification of normal price variation specified by GARCH process which was modelled to distinguish between impacts of good news and bad news, respectively.
[46] Source for power price data: www.ote-cr.cz

$$\varepsilon_{1,t} = \sigma_t z_t, \qquad z_t \sim NID(0,1), \tag{2}$$

presents normal stochastic process which captures ordinary daily changes resulting from matching of power supply and power demand, and $\varepsilon_{1,t}$ is also mean-zero innovation ($E[\varepsilon_{1,t} | \phi_{t-1}] = 0$). “Normal price variation is assumed to be normally distributed with a time varying conditional variance governed by a GARCH model” (Hellström et al. 2012: 7). GARCH (1,1) process is given by:

$$\sigma_t^2 = \omega_0 + \omega_1 \varepsilon_{t-1}^2 + \omega_2 \sigma_{t-1}^2, \tag{3}$$

and residual, $\varepsilon_{1,t}$, is defined as $\varepsilon_{1,t} = r_t - \mu_t$. The GARCH specification is expected to capture smooth changes in volatility and volatility clustering.[47]

The mean value of normal price variation, μ_t, reflects the day-of-week effect when includes variables representing lagged power returns from week and two weeks ago, respectively. It also incorporates the typical feature of electricity price behavior – mean reversion – when includes last day power return:

$$\mu_t = \alpha_0 + \alpha_1 r_{t-1} + \alpha_2 r_{t-7} + \alpha_3 r_{t-14},^{48} \tag{4}$$

therefore α_1 is expected to have a negative sign to work as mean-reversion process.

The jump innovation component, $\varepsilon_{2,t}$, representing the impact of irregular significant events has expected value equal to zero, $E(\varepsilon_{2,t}) = 0$. The jump innovation is derived from the jump size, $Y_{t,k}$, which is governed by a normal distribution with mean jump size θ and jump variance δ^2.

$$Y_{t,k} \sim NID(\theta, \delta^2) \tag{5}$$

$Y_{t,k}$ is the size of the k:th jump occurring during time interval (t-1,t). There is a possibility to have more jumps during such a time interval, so the whole jump component (J_t) influencing the power return during time interval (t-1,t) is sum of all jumps occurring in that interval:

$$J_t = \sum_{k=1}^{n_t} Y_{t,k}. \tag{6}$$

As a result the jump innovation takes the following form:

$$\varepsilon_{2,t} = J_t - E[J_t | \phi_{t-1}], \tag{7}$$

[47] In case of stocks there is expectation that large changes are followed by large changes while small changes are followed by small changes thus different size of volatilities are assumed to cluster in time and jump probability should be higher just in times of higher volatility.

[48] General form of μ_t parameterization looks like $\mu_t = \alpha_0 + \sum_{s=1}^{l} \alpha_s r_{t-s}$.

which corresponds to the classic form of residual and explicitly equals the difference between the sum of sizes of all n_t jumps during given time period and mean value of sum of sizes of all n_t jumps conditional upon past returns. The following equations will serve for computation of mean (θ) and variance (δ^2) of jump component which work as parameters of these equations.

The significant part of the model is way how to determine the number of jumps during a given time interval. Since most probably there is no jump during the given time interval and likelihood of consecutive jumps decreases with their number, the number of jumps cannot be governed by normal distribution, but Poisson distribution is more appropriate. A Poisson distribution is assumed to describe the arrival of a discrete number of jumps, $n_t \in (0, 1, 2, \dots)$ with a time-varying conditional intensity parameter λ_t[49] which is conditional on ϕ_{t-1}. The conditional probability mass function of n_t is given by

$$P(n_t = j|\phi_{t-1}) = \frac{\exp(-\lambda_t)\lambda_t^j}{j!}, \quad j = 0, 1, 2 \dots \tag{8}$$

λ_t presents jump intensity and from the definition of Poisson distribution follows that the expected number of jumps is equal to λ_t[50], $E[n_t|\phi_{t-1}] = \lambda_t$. So λ_t presents a key variable of the model and as a result the equation of λ_t gives the name of the EARJI model when dynamics governing the λ_t is specified in the following exponential autoregressive form:

$$\lambda_t = \lambda_0 + \gamma_1\lambda_{t-1} + \gamma_2\xi_{t-1}, \tag{9}$$

when the specification is called EARJI (1,1) and it is similar to GARCH (1,1) when the order of autoregressive lags and the order of moving average lags are equal to one. From the equation is clear that λ_t is autoregressive and it is dependent on its residuum, called a jump intensity residuum, from last period (ξ_{t-1}).[51] "The jump intensity residuum (ξ_{t-1}) is defined by

$$\begin{aligned} \xi_{t-1} &= E[n_{t-1}|\phi_{t-1}] - \lambda_{t-1} \\ &= \sum_{j=0}^{\infty} jPr(n_{t-1} = j|\phi_{t-1}) - \lambda_{t-1}, \end{aligned} \tag{10}$$

[49] Chan and Maheu (2002) also presented basic model with constant jump intensity when $\lambda_t = \lambda$.
[50] Mean and variance are both equal to λ_t in case of Poisson distribution.
[51] In Hellström et al. (2012) specified the time-varying jump intensity in logarithmic form $\ln(\lambda_t) = \lambda_0 + \gamma_1\ln(\lambda_{t-1}) + \gamma_2\xi_{t-1}$ but they did not specify how the logarithmic result is incorporated in subsequent equation where λ_t appears and in original models of Chan and Maheu (2002) and Maheu and McCurdy (2004) there is only linear form. Hellström et al. (2012) explains the using of logarithmic form in the way that "the exponential specification allows ξ_{t-1} to affect current λ_t asymmetrical, i.e., a shock of equal magnitude, positive and negative, have a different impact depending on the sign of γ_2. For example, for a positive γ_2 positive shocks captured by ξ_{t-1} have a larger impact on the current λ_t than negative shocks of equal magnitude" (Hellström et al. 2012: 8).

and "ξ_{t-1} represents the innovation to λ_{t-1} as measured ex post by the econometrician … the first term on the right hand side of (10) is our inference on the average number of jumps at time t-1 based on time t-1 information, while the second term in (10) is our expectation of the number of jumps using information at time t-2. Therefore, ξ_{t-1} represents the unpredictable component affecting our inference about the conditional mean of the counting process n_{t-1}" (Chan et al. 2002: 379). Or another definition: "ξ_{t-1} represents the change in the econometrician´s conditional forecast of n_{t-1} as the information set is updated" (Maheu et al. 2004: 762).

Based on Bayes rule[52] a filter is inferred which provides an ex post distribution for the number of jumps (n_t)

$$\Pr(n_t = j|\phi_t) = \frac{f(r_t|n_t = j, \phi_{t-1}) * \Pr(n_t = j|\phi_{t-1})}{\Pr(r_t|\phi_{t-1})}. \quad (11)$$

By term ex post is meant that calculation for number jumps at time t is performed after return r_t is observed. The whole term can be explained as probability of certain number of jumps at time t conditional on return from time t is equal to product of probability of this given return at time t ($f(r_t|n_t = j, \phi_{t-1})$) conditional on the certain number of jumps including past returns (given by (13)) and probability of this certain number of jumps ($\Pr(n_t = j|\phi_{t-1})$) based on Poisson distribution (given by (8)) and this product is divided by all possible scenarios which can return obtain based on number of jumps and past return ($\Pr(r_t|\phi_{t-1})$ given by (12)).[53]

The conditional density of returns, $\Pr(r_t|\phi_{t-1})$ is given by a mixture of distributions

$$\Pr(r_t|\phi_{t-1}) = \sum_{j=0}^{\infty} f(r_t|n_t = j, \phi_{t-1}) \Pr(n_t = j|\phi_{t-1}) \quad (12)$$

and it presents all possible scenarios of return at time t given by number of jumps and past returns where conditional density of returns is normal:

$$f(r_t|n_t = j, \phi_{t-1}) = \frac{1}{\sqrt{2\pi(\sigma_t^2 + j\delta^2)}} * exp\left(-0{,}5 * \frac{(r_t - \mu_t - \theta j + \theta\lambda_t)^2}{(\sigma_t^2 + j\delta^2)}\right).^{54} \quad (13)$$

---

52 P(A|B) = P(A)P(B|A)/P(B).

53 To get any solution would be impossible if we counted with possibility of infinite number of jumps, "in practice, we truncate the maximum number of jumps to a large value τ, so the probability of τ or more jumps is 0" (Chan et al. 2002: 380). In this study τ was chosen equal to 25 in accordance with Maheu et al (2004) and in practice the probability more jumps than 5 is negligibly small and almost equal to 0.

54 Although in Hellström et al. (2012) there is the time varying mean value of jump size, θ_t, in their equation of conditional density of return, it appears in their results as constant. The same inconsistency applies for variance of jump size, δ^2, when on contrary variance of normal volatility, σ_t, appears in the equation as constant. In accordance with their results and estimated model in Maheu et al. (2004), this study approaches to σ_t as time-varying variable and to θ and δ^2 as constants.

Normal price process is characterized by mean (μ_t) and variance (σ_t^2), while the jump component has own mean (θ) and variance (δ^2). The equation (13) presents modified probability density function of normal distribution which is expanded by parameters representing the jump component.

The construction of the likelihood function is based on equations (9), (11) and (12) and since we are interested in revealing actual jumps more than in probability of certain number of jumps, the study follows Hellström et al. (2012) and Maheu et al. (2004) and "considers actual jump to have occurred if the ex-post probabilities of at least one jump is larger than 0,5, i.e. $\Pr(n_t \geq 1|\phi_t) = 1 - \Pr(n_t = 0|\phi_t)$" (Hellstöm et al. 2012: 9). The ex-post probability of zero jumps is given by

$$\Pr(n_t = 0|\phi_t) = \frac{f(r_t|n_t = 0, \phi_{t-1}) \Pr(n_t=0|\phi_{t-1})}{\Pr(r_t|\phi_{t-1})}. \tag{14}$$

The output of the model is binary series with value 1 in case of occurring jumps. After determination of days with jumps, the process of distinguishing between positive and negative jumps follows based on the observed returns. This series is used as categorical variable in the second step of the model to estimate which factors cause the realization of the jump.

The last task of the first step is to determine unconditional values of σ^2 and λ since they are dependent on its lagged values and we need some startup values. The unconditional variance is given by

$$\sigma^2 = \frac{\omega_0}{1-\omega_1}, \tag{15}$$

while in accordance with Chan et al. (2002) and Maheu et al. (2004) is set that $\xi_1 = 0$ and unconditional jump intensity is equal to

$$E[\lambda_t] = \frac{\lambda_0}{1-\gamma_1}.\ ^{55} \tag{16}$$

[55] In Hellström et al. (2012) they did not define any unconditional and startup values and from their results it is possible to deduct that they had to use some different definition for unconditional jump intensity because they have λ_0 with negative sign and as a result the unconditional jump intensity would be also with negative sign and from the equation (9) follows that subsequently jump intensity in every time t would be with negative and such results do not make sense.

3.2.2. Second step

Dependent variable

As was said the output from the first part of the model is used as a dependent variable for the second part which studies factors causing jumps in price of electricity. For this purpose a categorical variable was created according to an identified jump:

$$y_t = \begin{cases} -1, \text{identified negative jump} \\ 0, \text{no identified jump} \\ 1, \text{identified positive jump} \end{cases}$$

which serve as dependent variable in ordered probit model as well as it was in Hellstöm et al. (2012). The data about spot power price come from OTE sources and it presents daily day-ahead prices from auction managed by OTE during the period from 19.7.2010 to 30.4.2014. This period was chosen because of data availability of other variables which are available mostly from 2010 and the first complex data about renewables from Germany are available from 19th July 2010.

There is important to say that the minimal trading period of power in the Czech Republic is one hour and hourly data about prices are available. The benefits of hourly data would be clearly such that volatility of hourly prices would be even higher with more jumps and time series would be longer, of course. But on the other side the day-ahead market is kind of futures market since traders make deals based on prediction of fundamentals for that day. And this prediction can deviate from real values which this study uses in its calculations. The idea is such that exact hourly prediction is very difficult to achieve and it could deviate from real values. As a result the day-ahead price per given hour would not reflect real values but false prediction in case of large deviation, and jumps could not be explained. On contrary it assumes that in sum a prediction for a whole day is much more precise and hourly deviations are in sum close to zero for the whole day. For example it is difficult to predict in what hour exactly clouds disappear or wind starts blowing to renewables generate more power. On contrary the prediction for high power generation from renewables should be more precise.

The weekend data were excluded from time series since during weekend the price always decreases and there might always be a jump between Sundays a Mondays, thus weekend data were omitted not to distort the results. Moreover during Christmas holidays 2012 the Czech power price experienced negative prices in case of the day-ahead product, in respect to the indefinable logarithm of negative number these negative prices had to be changed into positive numbers very close to zero. The power price did not experience a jump during the time of negative price, thus the results will not be influenced.

Independent variables

The potential causes for jumps in electricity price are connected with independent variables of the model with one exception which is dummy variable for market coupling with Hungary which divides time series into two parts.

In accordance with Hellström et al. (2012) temperature was chosen as one of explanatory variables, which assumes a significant decrease in temperature causes an increase in power demand, specifically during winter months. The increase in temperature has the opposite impact at least in case of mild temperature but in case of really high temperatures demand for power could increase with higher temperatures but not enough for a price jump. The question is whether a significant decrease in temperature can cause a jump in the Central European conditions where winters are not so cold in comparison with Scandinavian region. The data about temperature come from OTE, which publishes average daily temperature data to count consumption of small customers.

Another explanatory variable is connected with the fact that the Czech Republic is only a price taker in case of power price.[56] The size of German power market and volume of the Czech electricity export to Germany means that Germany presents a power price maker for the Czech market. For that reason Germany national holidays[57] were chosen as independent variable instead of Czech national holidays.[58] Since many holidays of the Czech Republic and Germany are common, the effect of holiday had to be tested on special holidays of individual countries. While nationwide holidays in Germany, not celebrated in the Czech Republic, always have an impact on the Czech price, the Czech special holidays like St. Venceslass have an unobservable impact. The impact of Holidays is expected to decrease the demand for electricity as most of high power-consuming industries stop or at least decrease its production. Subsequently the drop in power demand is expected to cause a jump in downward direction.

The German holiday's variable relates to another dummy variable representing the day which follows after Holidays.[59] The idea is straightforward – when the demand returns back to

---

[56] According to own calculation, correlation between the day-ahead price of EEX and the day-ahead price of OTE is equal to 95,3 % during monitored period from 19.7.2010 to 30.4.2014.

[57] Among Bank holidays were chosen only nationwide legal holidays, not legal holidays only for some provinces, in particular – New Year, Good Friday, Easter Monday, Labor Day, Ascension, Whit Monday, Day of German Unity, Christmas and St. Stephen´s Day.

[58] Some German holidays are also holidays for other Western Europe countries, especially religious holidays like Good Friday, Ascension, and Whit Monday. Therefore the effect of such holidays is even stronger when more countries have holidays.

[59] The variable is called "Dayafter" in the model.

its “normal”, so does the price. Therefore if power price jumped downwards because of holiday, after the holidays end, price should revert back through a jump to its original level and undertake the mean-reversion process.

The model includes a dummy variable representing market coupling with Hungary. Thus this variable divides the monitored period into two parts. Unfortunately the monitored period cannot be divided into three periods to distinguish the era before market-coupling with Slovakia because market-coupling with Slovakia was launched in 2009 and data of this study start in summer 2010. Hellström et al. (2012) proved that market structure matters when probability of power price jump was changing in respect to enlargement of Nord Pool by Finland and Denmark. The enlargement was moving with capacity constraint and it was increasing or decreasing the difference between available capacity and power load. Regarding market-coupling with Slovakia, it hardly can be spoken of capacity constraint as the Czech Republic belongs to significant power exporters and Slovakia has a balanced its power supply and its power demand.[60] The interconnection of both power markets is almost perfect when both markets coupled in 91,7 % monitored days (it means that they coupled in all 24 hours of 91,7 % days). Market-coupling with Hungary is a different topic since there is congestion between the Slovakian and Hungarian power grid. As a result a limited cross-border capacity hinders full interconnection of both areas and Hungarian power market is able to influence the rest power markets only in a limited way.[61]

The previous parts showed that significance of power generation from renewables is increasing. Their growth moves the merit order to the right and therefore it decreases the market power price. Any change in power generation from renewables moves the merit order from day to day and it also causes power price changes. The assumption is such that a large change in power generation from renewables can cause a large change in power price, even a jump of power price. Since the Czech power price follows the German power price and at the same time installed capacity of renewable energy sources is much higher in Germany than in the Czech Republic, the German power generation from renewables in a form of logarithmic rate of change acts as one of explanatory variables. Figure 9 depicts the growth of installed capacity of wind and solar power – at the end of 2013 installed capacity of wind and solar power totaled

[60] In 2013 Slovakia was a net importer when net import totaled 91 GWh that presents 0,003 % of Slovakian power production (source: www.sepsas.sk)

[61] Complete day market-coupling between Hungary and Czech-Slovakian power markets happened only in 24,2 % days, from the start of market-coupling with Hungary to 30th April 2014.

68 GW.[62] One important feature of power generation from renewables relates to their volatility, e.g., in 2013 annualized volatility of solar and wind power generation was equal to 905 %. So high volatility is even higher than annualized volatility of the Czech power price which counted without weekends 513 % during the same period.

The last explanatory variable is connected again with the German power market. The volume of the Czech power export was mentioned in the previous text[63] and figure 4 offers a summary of cross-border trading volumes between Germany and its neighbors. From the look at the figure it is obvious that the Czech power market belongs to the most important power exporters to Germany. But there is one aspect which hinders using real power export data as explanatory variable, real export data refer to measured flow of electricity through interconnection between individual power grids. This real volume is not known during the day-ahead market at all, and as such it cannot have an impact on the day-ahead power price. Much more important for the day-ahead market is the used capacity for transmission of electricity to given neighboring power grid since it gives evidence how much electricity was sold for export. Therefore daily predictions of used capacity published by ČEPS in a form of logarithmic rate of change represents cross-border trade with electricity. During the monitored period, used capacity for export totaled 15,2 TWh to Austria, 31,3 TWh to TenneT, 21,4 TWh to 50Hertz, 37,2 TWh to Slovakia, and 0,488 TWh to Poland.[64]

There arises a question why Czech temperature is used as an explanatory variable, when other explanatory variables are so connected with Germany. The reason is that Czech temperature is official temperature published by OTE for counting purposes and there is no single one officially published German temperature, moreover both temperatures are very close with similar changes.

Missing independent variables

There are fundamental variables, potentially causing price jumps, which someone could miss in the model. Hellström et al. (2012) used a change in power generation from nuclear power plants. Generally, the outages of big power plants belong to favorite explanatory variables of price dynamics. But this idea can work only in situation when power market is situated close to its capacity constraint when an outage of big source can cause a need for import

[62] For comparison, total installed power generation capacity in the Czech Republic equaled to 21 GW at the end of 2013. And solar and wind power generation capacity totaled to 2,4 GW (source: Yearly report on the operation of the Czech electricity power grid 2013)

[63] In last three years Czech net power export oscillates around 17 TWh per year which counts approximately 21 % of power generation in the Czech Republic (source: Yearly report on the operation of the Czech electricity power grid 2013).

[64] Source of data: www.ceps.cz.

of electricity from neighboring countries. Currently, during several years lasting economic stagnation in Europe, the state of the European power sector is far away from its capacity constraint. Moreover the growth of power generation from renewables moves the capacity constraint upwards. In such situation of the European power market, when unexpected outage happened, the source is very quickly substituted. This outage can impact only the intra-day market since it takes a few hours to launch power generation from reserve sources. Until the next day which is connected with the day-ahead price, which is in our interest, the outage has to be replaced. As a result the day-ahead price cannot be influenced into such extent that price would jump.

4. Empirical results

The first step of the model should reveal jumps in time series of the Czech power price. But during the implementation phase the model has emerged to be unsuitable to properly indicate jumps in power price. The problem comes out from the fact that the model completely proceeds from past values with the exception of logarithmic return and as a result it predicts high probability of a jump after the first jump occurred, thus it is able to predict mostly only a reverse jump. The problem is connected with the specific nature of the power market and its difference comparing to the stock market. On the stock market the reason for a jump usually does not come up suddenly from nothing, before the jump it is possible to expect uncertainty on the market and resulting higher volatility. On contrary the power price does not need any uncertainty on the market to perform a jump, the fundamental reason for a jump suddenly emerges as well as it suddenly disappears. After a reverse jump, the power price can perform relatively calm development while stock can undertake very volatile period.

The time-varying jump intensity (λ_t) presents the key variable of model since it oscillates with the model in case of a jump, but it is also completely dependent on the past. The model could be more jump sensitive if mean jump size (θ) and variance of jump size (δ^2) were time-variant. Chan et al. (2002) offer extensions of the model when these parameters become time-variant variables, but it would not solve the problem anyway, because both variables still would be dependent only on past.

The only solution is to base the model on fundamental factors, but it would completely change the model which is based only on time series of power price. The previous parts of this thesis showed uniqueness of power market and a model, which does not reflect the unique nature of power market, cannot work properly. There are always objective reasons to jump realized, these factors are studied in the second step of the model. A model sometimes cannot be just transfer from one environment to another environment, and this is the case. The main reason why the model does not work properly is the abruptness of arrival of power jump and of its reverse jump without prior indication in price development. In that case a model based on time series is able to predict only reverse jumps.

Because of unsuitability of the first step of the model there arises a question how to reveal jumps in power price time series. Boogert et al. (2007) offer solution when they set a fixed price in euros for MWh. This does not seem as a suitable solution since power price includes a trend and price can cross the boundary for a long time. Instead, this study will use once calculated logarithmic return which takes trends into consideration. A daily logarithmic return of 25% was stated as a firm boundary for definition of a jump,[65] the value was chosen to include all large changes in the power price. With this boundary 91 jumps in 987 observations were found, that equals to 9,22 % of cases. 48 of found jumps were negative while only 43 jumps were positive. It means that several negative jumps were followed by another negative jump which could be caused by consequent holidays.

Table 3: Jump frequencies

Jump	Freq.	Percent	Cum.
-1	48	4.86	4.86
0	896	90.78	95.64
1	43	4.36	100.00
Total	987	100.00	

In table 4 you can find descriptive statistics of explanatory variables, average daily temperature was moving between -15,2 °C and 25,9 °C during the monitored period, the power generation from renewables decreased by 202 % at maximum while increased by 232 % at maximum from day to day. The highest power generation from renewables counted 578 GWh on the 24th December 2013, while the lowest counted only 14,4 GWh on the 26th November 2010. The maximum percentage change in case of power export achieved almost 63 %, the highest amount of capacity to export 73,8 GWh to Germany and Austria was used on the 1st January 2011.

[65] The value is, of course, questionable and it can be chosen different values.

Table 4: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Temp	988	7.984008	8.055398	-15.2	25.9
Holidays	988	.0263158	.1601538	0	1
Dayafter	987	.0202634	.1409715	0	1
CouplingHU	987	.4326241	.4956909	0	1
Renewables	987	.0005906	.5456879	-2.025284	2.326207
Export	987	-.0018815	.1260162	-.5300062	.6276791

Through ordered probit model coefficients of explanatory variables for dependent variable representing power price jump were estimated. The results can be found in Table 5, but in general results of ordered probit model are difficult to interpret. "The coefficients give the signs of the partial effects of each explanatory variable on the response probability, and the statistical significance of explanatory variable is determined by whether we can reject H_0: $\beta_j = 0$ at a sufficiently small significance level" (Woolridge. 2012: 590). At first we need to test the significance of the model, this test can be done through Likelihood ratio test which is an analogy to F-test in case of linear models. "The Likelihood test is based on the difference in the log-likelihood functions for the unrestricted and restricted models. The idea is this: Because the Maximum likelihood estimation maximizes the log-likelihood function, dropping variables generally leads to a smaller—or at least no larger—log-likelihood … the question is whether the fall in the log-likelihood is large enough to conclude that the dropped variables are important" (Woolridge. 2012: 589). In Table 5 it is possible to find the results of the Likelihood ratio test based on which we can refuse zero hypothesis about insignificance of the model, thus we can declare that the model is significant.

In the results the column P>(z) presents "the probability the z test statistic (or a more extreme test statistic) would be observed under the null hypothesis that a particular predictor's regression coefficient is zero, given that the rest of the predictors are in the model. For a given alpha level, P>|z| determines whether or not the null hypothesis can be rejected. If P>|z| is less than alpha, then the null hypothesis can be rejected and the parameter estimate is considered statistically significant at that alpha level" (IDRE. web). Based on z test statistic null hypotheses about explanatory variables representing German Holidays and the following Dayafter and more importantly null hypothesis about explanatory variable representing power generation from Renewables can be rejected, all three variables achieved 99% significance level

Table 5: Estimation results from the ordered probit model

```
Iteration 0:   log likelihood = -366.53547
Iteration 1:   log likelihood = -257.83422
Iteration 2:   log likelihood =  -250.8993
Iteration 3:   log likelihood = -250.83655
Iteration 4:   log likelihood = -250.83654

Ordered probit regression                         Number of obs   =        987
                                                  LR chi2(6)      =     231.40
                                                  Prob > chi2     =     0.0000
Log likelihood = -250.83654                       Pseudo R2       =     0.3157
```

Jump	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
Temperature	.0123196	.0221577	0.56	0.578	-.0311087	.0557479
Holidays	-1.925647	.261815	-7.35	0.000	-2.438795	-1.412499
Dayafter	2.723262	.3222675	8.45	0.000	2.091629	3.354895
CouplingHU	-.0070456	.1214216	-0.06	0.954	-.2450276	.2309364
Renewables	-1.203193	.1207829	-9.96	0.000	-1.439923	-.9664631
Export	.4026032	.4565971	0.88	0.378	-.4923107	1.297517
/cut1	-2.136051	.1174377			-2.366224	-1.905877
/cut2	2.228188	.1241508			1.984857	2.471519

These results are confirmed by performing the average marginal effect (AME) which is more convenient for interpretation of results,[66] results of AME are presented in Table 6 and Table 7.

On the contrary, variables representing temperature, market coupling with Hungary and used export capacity to Germany and Austria appear to be insignificant. It has shown that temperature in the Central European area does not have a jump impact on the power demand, but even in Hellström et al. (2012) only a positive jump in temperature was negatively connected with a positive power price jump which means that high growth in temperature decreased the probability of jump growth in power price. Unsurprisingly, market coupling with Hungary does not indicate any influence on the probability of jump since between the Slovakian and the Hungarian power grids only limited transmission capacity is situated. It could be more interesting to study the relationship between market coupling and power price jumps from the respect of Hungarian power price since after decoupling with the Czech and Slovakian market area the growth of power price almost always follows.[67] The result does not correspond with the results of Hellström et al. (2012) which found a significance in joining of Finland and Denmark to Nord Pool. But Nord Pool presents completely different market area when its

[66] See Woolridge (2012) to get more about the average marginal effect.

[67] From 452 cases of decoupling of Hungary from the Czech and Slovakian market area during monitored period only one presents the case of decoupling and lower Hungarian price, it happened on the 11th March 2013.

Table 6: Marginal effects of the ordered probit model in case of negative jump

```
Marginal effects after oprobit
      y  = Pr(Jump==-1) (predict, outcome(-1))
         =  .01641591
```

variable	dy/dx	Std. Err.	z	P>|z|	[95% C.I.	]	X
Temp	.0002986	.00033	0.91	0.364	-.000347	.000944	7.97477
Holidays*	.3806803	.09433	4.04	0.000	.195788	.565573	.026342
Dayafter*	-.0188419	.00464	-4.06	0.000	-.027932	-.009752	.020263
Coupli~U*	.0009106	.00506	0.18	0.857	-.008999	.01082	.432624
Renewa~s	.0494039	.009	5.49	0.000	.031766	.067042	.000591
Export	-.0162709	.01879	-0.87	0.387	-.0531	.020558	-.001881

(*) dy/dx is for discrete change of dummy variable from 0 to 1

Table 7: Marginal effects of the ordered probit model in case of positive jump

```
Marginal effects after oprobit
      y  = Pr(Jump==1) (predict, outcome(1))
         =  .01251984
```

variable	dy/dx	Std. Err.	z	P>|z|	[95% C.I.	]	X
Temp	-.0002365	.00025	-0.93	0.353	-.000735	.000262	7.97477
Holidays*	-.0142333	.00401	-3.55	0.000	-.022084	-.006383	.026342
Dayafter*	.6666184	.10941	6.09	0.000	.45217	.881067	.020263
Coupli~U*	-.0007164	.00396	-0.18	0.857	-.008483	.00705	.432624
Renewa~s	-.0391235	.00828	-4.72	0.000	-.055361	-.022886	.000591
Export	.0128851	.01482	0.87	0.385	-.016168	.041938	-.001881

(*) dy/dx is for discrete change of dummy variable from 0 to 1

members have a different structure of power generation sources.[68] These different power generation structures supplement each other and in combination with the difference in their demand-available capacity ratio the enlargement by another country can have a larger impact on probability of power price jump than in the case of joining of Hungary to the market coupling of the Czech Republic and Slovakia.

A different versions of used power export capacity, like used net export capacity, were tested, but neither of them was showed as significant and their replacements had no impact on coefficients of other variables. The insignificance could be connected with the still limited transmission capacity between individual power grids and from that resulting lower volatility of this variable since the transmission capacity set boundaries for the power export. The used power export capacities are more stable than for example renewable power generation.

[68] Hellstrom et al. (2012) describe the structure of power generation sources of individual countries more detailed.

In Tables 6 and 7, which represent marginal effects of the estimated ordered probit model, we can find that in case of holidays the probability of negative jumps increases, while the probability of positive jumps decreases. These findings correspond to the assumption of fall in power demand when most people have a day-off from their jobs. The opposite sign in case of variable representing the day following after holidays confirms the mean-reverting process which results from restoration of power demand when people get back to their jobs.

The most interesting finding is connected to power generation from renewables whose impact on power price jumps was the main aim of this study. Marginal effects in Tables 6 and 7 confirm that power generation from renewables have a significant impact on the probability of jumps, more precisely the big growth in the power generation from renewables increases the probability of a negative jump while it decreases the probability of a positive jump. This finding is in accordance with the theory of the merit order representing non-linear power supply. The growth of renewable energy in power system effects the merit order by moving the power supply to the right which results in a decrease in power price. Therefore the large change in the power generation from renewables increases the probability of fall in the power price which confirms the assumption stated in the introduction of this thesis.

Suitability of the ordered probit model can be proved not only by Likelihood ratio test, but also by view on table 8 which depicts the predicted probabilities of the estimated ordered probit model. Compare the mean results with numbers in Table 3 which depicts the jump frequencies. The mean predicted probabilities of individual states (negative jump, no jump, and positive jump) correspond to actual percentage distribution of jumps in whole monitored period.

Table 8: Predicted probabilities of the ordered probit model

Variable	Obs	Mean	Std. Dev.	Min	Max
p1oprobit	987	.0484521	.0977938	2.24e-08	.7838463
p2oprobit	987	.9076363	.1327823	.1365616	.9712912
p3oprobit	987	.0439116	.1096654	1.23e-07	.8634384

Summary

The aim of my thesis is to find factors which cause the non-regular price moves, called power price jumps, in the case of the Czech Republic. For this purpose a two-step model is chosen. The first part is presented by the GARCH-EARJI model, firstly used for a power market case in Helström et al. (2012) and originally developed by Chan and Maheu (2012) to reveal jumps on the stock market. The following second step should use the output of the GARCH-EARJI model as a dependent variable in the ordered probit model.

This study differs from the above mentioned paper written by Hellström at al. (2012) by a dissimilar choice of explanatory variables for the second step. They both use only an explanatory variable representing temperature and a dummy variable reflecting enlargement of market-coupling area, respectively. National holidays in Germany, the day following after the holidays, used transmission capacity to Germany and Austria are chosen as factors, which could cause power price jumps and at the same time the thesis puts a special emphasis on the power generation from renewables whose data come from Germany, so the power generation from renewables also belongs to explanatory variables of the model. Almost all explanatory variables are somehow connected with Germany; the Czech power market works only as a price taker and follows the German price and their correlation was equal to 95,3 % in 2013.

The estimation of the GARCH-EARJI model is applied in a period starting on 19th July 2010 and ending on 30th April 2014. Weekend data are excluded from all-time series since power price jumps almost always happen between Sunday and Monday. Unfortunately the application of the GARCH-EARJI model on the power market case has shown as unsuitable. This problem is connected with the basic feature of the model which completely proceeds from past values and that does not correspond with the nature of the power market. The model also does not reflect a way how the power market differs from the stock market. Before price jumps, uncertainty and resulting higher volatility can be expected on the stock market. On the contrary, power price does not show any uncertainty on the market before performing a jump, the fundamental reason for a jump suddenly emerges as well as it suddenly disappears. The past dependent GARCH-EARJI model is able to predict only reverse jumps after the first jump had occurred. A model, which does not reflect nature of the power market and which is not based on fundamental factors of the power market, cannot properly predict the power price jump. A model completely dependent on past power price returns is not suitable for the power market.

Without proper results from GARCH-EARJI model there is a need for an alternative way how to determine jumps within power price time series. A daily logarithmic return of 25 %

is chosen as a firm boundary for definition of jump, with this boundary 91 jumps in 987 observations are found. The found jumps are distinguished into negative jumps (number -1), positive jumps (number +1) and observations without jumps (number 0).

Based on the results from the ordered probit model it could be said that holidays in Germany increase the probability of a negative jump in the Czech spot power price as a result of fall in power demand because most people have a day-off from their jobs. On the contrary, the variable representing the day following after holiday shows its significance when it increases the probability of a positive jump because of the restoration of power demand when people get back to their jobs. The opposite sign of coefficient of this variable in comparison with the coefficient for holidays presents a mean-reverting process, which belongs to basic features characterizing power price.

One of the main goals of this diploma thesis is to prove the hypothesis that **growth of power generation from renewables on the side of supply have a negative impact on the price of electricity and its volatility causes power price jumps. The results from the ordered probit model confirm this assumption and proves the hypothesis.** According to the estimated coefficient it is possible to state that the growth of power generation from renewables increases the probability of negative jumps. The growth of renewable energy in power system effects merit order by moving power supply to the right which results in a decrease in power price. Annualized volatility power generation from renewables in 2013 achieved a level 905 %, such a high volatility causes the dynamics of power price when the most expensive power sources in merit order have to be shut down because of high power generation of renewables which moves the whole supply curve to the right.

Another aim was to find out, **if the integration process in the form of market coupling has some jump impact on the final power price.** Since the model could be estimated only on the data from the 19th July 2010, the effect of market-coupling could be tested only on joining of Hungary to already working common market area of the Czech Republic with Slovakia which these two countries established in 2009. In the estimated results the variable representing market coupling with Hungary does not indicate any influence on the probability of a jump because of limited transmission capacity between Slovakian and Hungarian power grids. Therefore **the results invalid the assumption that market coupling has any jump effect in the Czech power price case.** It could be more interesting to study the relationship between market coupling and power price jump from the respect of Hungarian power price since after decoupling with the Czech and Slovakian market area growth of Hungarian power price almost always follows.

The last assumption refers to power export from the Czech Republic to both German power grids (Tennet and 50Hertz) and the Austrian power grid; these grids form one market area which the Czech price follows. This fact in combination with volume of power export from the Czech Republic, which totals around 21 % of the Czech power production, means that the Czech power export belongs to important features of the Czech power market. The stated hypothesis assumes that **a significant change in the Czech power export to Germany can cause jumps in electricity price on the demand side.** Since the real export is not related to the day-ahead market but reflects only a real-time transfer within the European market and its congestion between individual power grids, it is needed to choose another variable representing power export. The used power capacity between power grids is chosen as the variable representing power export; the value should be reflected in the day-ahead power price. **According to the results of the estimated model the power export has no significant impact on the probability of a power price jump. Thus the hypothesis about the jump impact of power export on power price is proved to be invalid in the Czech Republic case**. This is probably caused by limited transmission capacity between the individual power grids and resulting lower volatility of power export since transmission capacity set boundaries of power export.

The last explanatory variable influencing power price is presented by temperature but there is not found any significant causality between this variable and the probability of power price jump. The Central European area belongs to a mild climatic zone where temperature does not achieve so extreme values which would cause power price jump.

In sum, the aim of my thesis is to find factors which cause the power price jumps in the case of the Czech Republic. The goal is fulfilled when the thesis reveals a significant influence of German power generation from renewables and at the same it confirms the assumption of the impact of Germany national holidays on the power price dynamics when at first holidays cause a negative price jump and then the reverse jump follows after the end of these holidays. On contrary, the influence of temperature, market coupling with Hungary and used transmission capacity are found as insignificant regarding their impact on power price jump in case of the Czech Republic.

Following research of power price dynamics should focus on creation of a model which would reflect fundamental conditions of the power market. A model sometimes cannot be just transferred from one environment to another one, and the GARCH-EARJI model is a good example. The complete trading process in the power market is operated only by professional and so it is not subject to psychology so much as for example stock market. The power market is distinguished by many unique features which has to be reflected during research. This thesis contributed to the recent level of knowledge by findings answering the question how is power price dynamics influenced by the growing power generation from renewables but there are many other topics. In quickly developing power market, which is strongly influenced by the government and the EU authorities, new interesting elements like new power storage technologies, planned growth of pumped storage plants, flow-based method for transmission of electricity through all Europe, or new segment in the British power market – capacity market are emerging. All these new-coming elements will need further research.

Bibliography

Boogert, Alexandr and Dupont, Dominique. When supply meets demand: the case of hourly spot electricity prices. *Birkbeck Working Papers in Economics and Finance*, March 13, 2007, 1 – 22.

Bierbrauer, Michael, Menn, Christian, Rachev, Svetlozar T., Trück, Stefan. Spot and derivative pricing in the EEX power market. *Journal of Banking & Finance*, 2007, Vol. 31, 3462 – 3485.

Cheminišec, Igor, et al. 2010. *Obchod s elektřinou*. CONTE spol. s.r.o. Praha.

Chan, Wing H. and Maheu, John M. Conditional Jumps in Stock Market Returns. *Journal of Business & Economic Statistics*, July 2002, Vol. 20, No. 3, 377 – 389.

Engle, Robert. GARCH 101: The Use of ARCH/GARCH Models in Applied Econometrics. *Journal of Economic Perspectives*, 2001, Vol. 15, No. 4, 157 – 168.

Hellström, Jörgen, Lundgren, Jens, Yu, Haishan. Why do Electricity Prices Jumps? Empirical Evidence from the Nordic Electricity Market. *Energy Economics*, November 2012, Vol. 34, Issue 6, 1 – 22.

Huisman, Ronald and Maheu, Ronald. Regime Jumps in Electricity Prices. Energy Economics, 2005, Vol. 25, 425 – 434.

Kolektiv autorů. 2011. *Trh s elektřinou: Úvod do liberalizované energetiky*. Asociace Energetických Manažerů.

Lucia, Julio J. and Schwartz, Eduardo S. Electricity prices and the power derivatives: Evidence from the Nordic power exchange. *Review of Derivatives Research* 5, 2002, 5 – 50.

Maheu, John M. and McCurdy, Thomas H. News Arrival, Jump Dynamics, and Volatility Components for Individual Stock Returns. *The Journal of Finance*, April 2004, Vol. 59, No. 2, 755 – 793.

Meyer-Brandis, Thilo and Tankov, Peter. Multi-factor jump-diffusion models of electricity prices. *International Journal of Theoretical and Applied Finance*, 2008, Vol. 11, No. 5, 503 – 528.

Myung, In Jae. Tutorial on maximum likelihood estimation. *Journal of Mathematical Psychology*, 2003, Vol. 47, 90 – 100.

Woolridge, Jeffrey M. 2012. Introductory Econometrics: A Modern Approach. Cengage Learning; 5 edition.

Electronic sources

EC. *Directive 2009/28/EC on the promotion of the use of energy from renewable sources*. Available: http://europa.eu/legislation_summaries/energy/renewable_energy/en0009_en.htm (3.8.2014).

ERÚ. *Yearly report on the operation of the Czech electricity power grid 2013*. Available: http://www.eru.cz/documents/10540/462820/Annual_report_electricity_2013.pdf/34a35d27-9c58-4c79-99d1-f0fbc5eac06a (31.7.2014).

NY Times. *Germany Moves Forward on Renewable Energy Plan*. Available: http://www.nytimes.com/2014/04/09/business/international/germany-moves-forward-on-renewable-energy-plan.html?_r=0 (13.8.2014).

Ihned. *Nové soláry přijdou o podporu. Sníží se i příspěvek na obnovitelné zdroje*. Available:

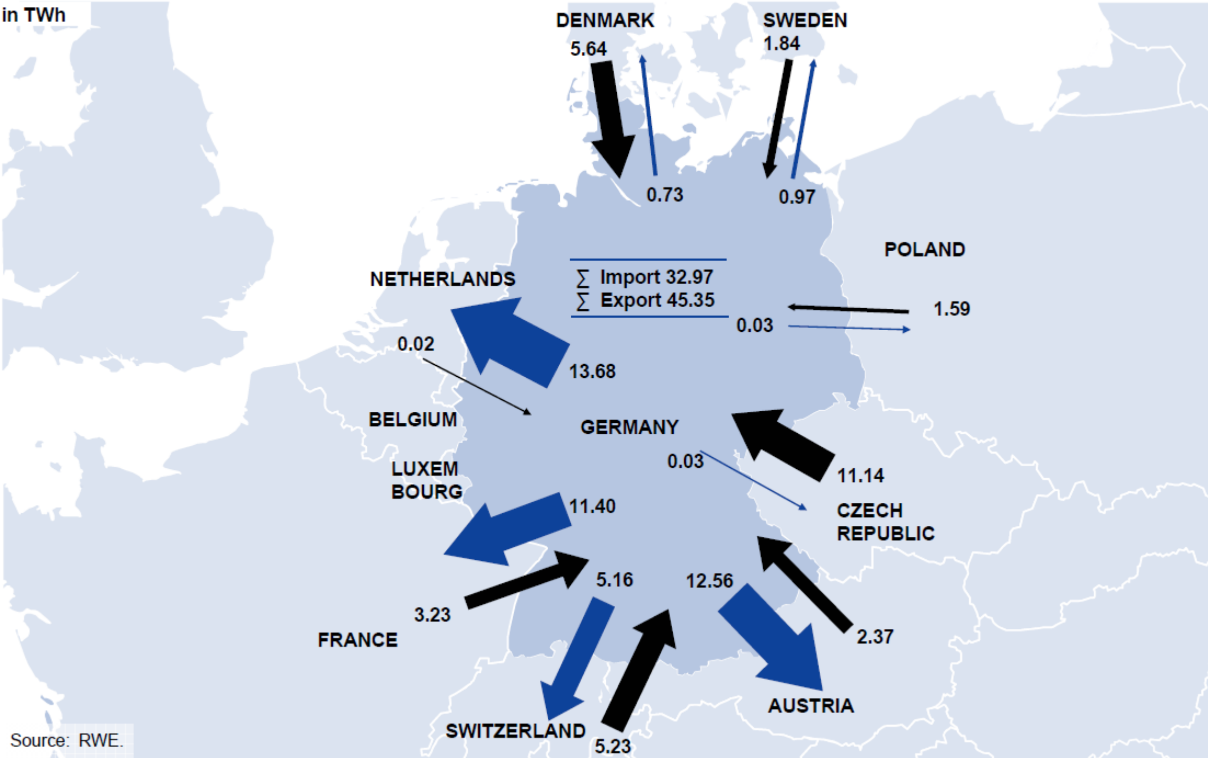
http://byznys.ihned.cz/c1-60715770-nove-solary-prijdou-o-podporu-obnovitelne-zdroje (14.8.2014).

IDRE. *Stata Annotated Output: Probit Regression*. Available:

http://www.ats.ucla.edu/stat/stata/output/Stata_Probit.htm (8.8.2014).

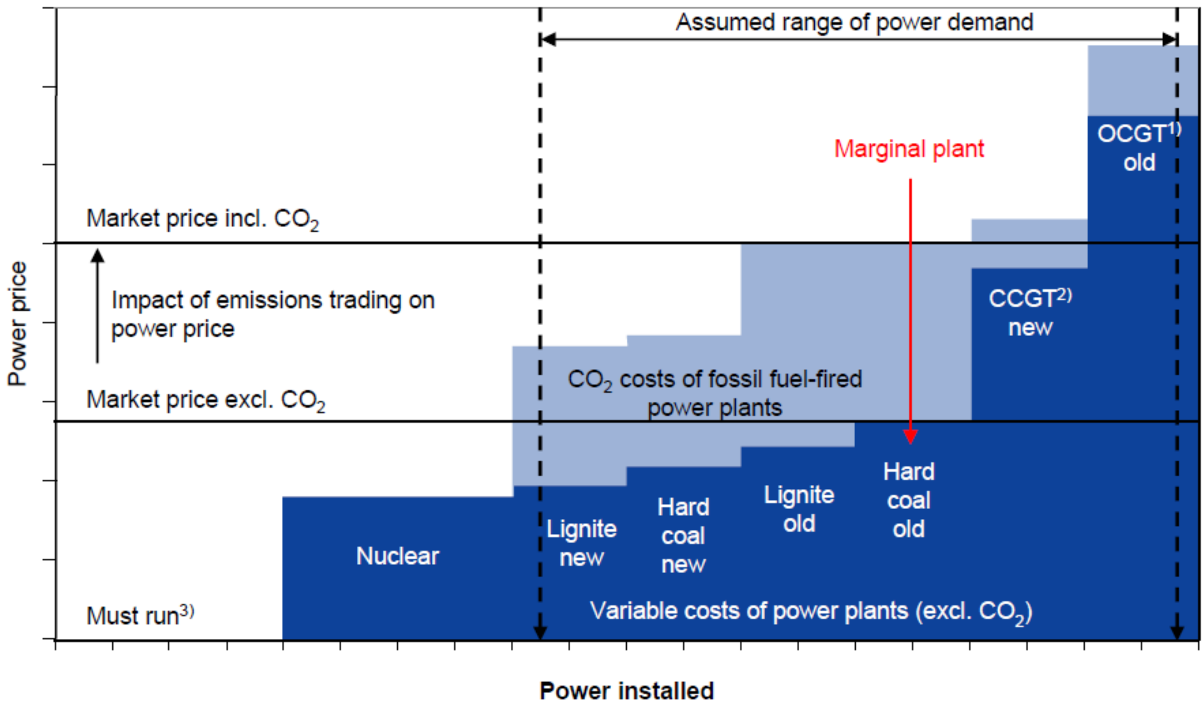
Appendix

Figure 4: Import/Export of electricity 2007 - Germany



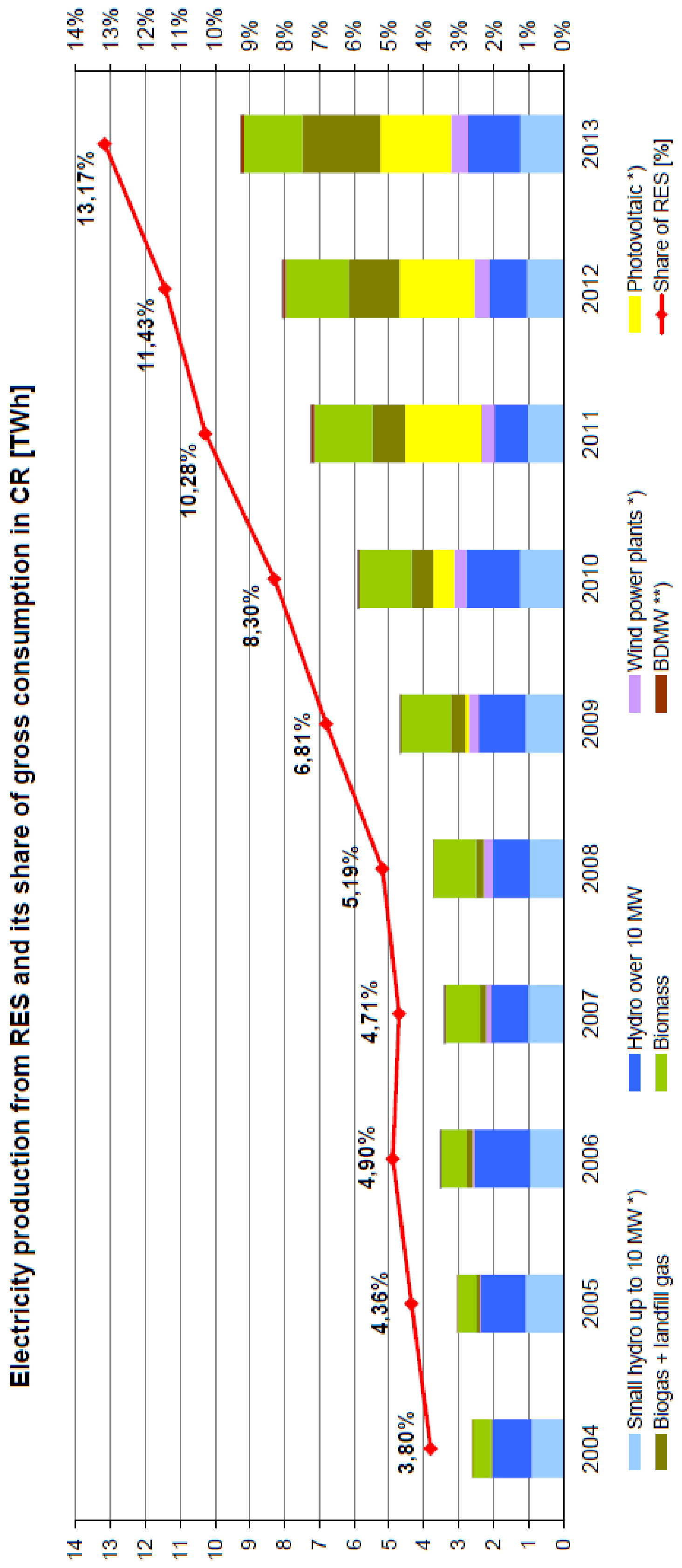
Source: www.rwecom.online-report.eu

Figure 5: Power Production Merit Order - Germany



Source: www.rwecom.online-report.eu

Figure 13: Development of production from renewables and its share on gross power consumption



Source: Yearly report on the operation of the Czech electricity power grid 2013