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System Imbalance Forecast

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Declaration

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

In Prague 26. 11. 2016 Štěpán Kratochvíl

Abstract

This thesis deals with the optimization of the BRP imbalance in the opposite direction to the system imbalance by the change of the output of the power plant. BRP imbalance optimization is a part of the energy market together with a long-term trading future or forwards contracts, midd-term day-ahead market and short-term intra-day and balancing market as well. BRP imbalance optimization is special in the Czech Republic by the ability of the BRP to change its imbalance in order to gain profit from achieving the opposite direction to the system imbalance.

Therefore, it is needed to forecast the average system imbalance value with the highest prediction for BRP optimization. The objective of the thesis is developing a forecast model, which recommends the optimization of the BRP imbalance in order to gain profit. Lack of the state-of-the-art papers is the reduced usage of the data inputs. There are a lot of factors that influence the system imbalance and often create sudden step changes in the system imbalance. Therefore, forecasted model includes multiple exogenous variables, which can explain and thus forecast these changes. Input exogenous variables are used both in their numeric values and in the differential values. Differential values can be obtained by deduction of the neighbouring values of the input variable or the difference between planned and actual value of the exogenous variable as well.

The forecast of the system imbalance is not needed in the point forecast as the concrete value of the system imbalance is not necessary for the optimization of the BRP imbalance. Therefore, I define the intervals of the system imbalance, for which is be the forecast made. Thresholds of these intervals have to be optimized carefully to utilize all the information from the input variables. I calculate the profit and loss resulting from the optimization to evaluate the BRP imbalance optimization. Opportunity costs result from the keeping of the power reserve for the optimization. It has to be kept in mind as these costs can be higher than the profit from the optimization. Results of the forecasted model are compared with the state-of-art and widely spread used ARMA model, which is significantly overcome by our proposed model.

Keywords:

System imbalance, balance responsible party, exogenous variable, interval distribution, forecast

Abstrakt

Dizertační práce se zabývá optimalizací dosažení protiodchylky subjektu zúčtování vzhledem k systémové odchylce. Dosažení odchylky subjektu zúčtování je jedna z částí energetického trhu, který dále umožňuje dlouhodobé obchodování, jako jsou future nebo forward kontrakty, středně dobé obchodování, jako je spotový trh a krátkodobý vnitrodenní a vyrovnávací trh. Možnost spekulace subjektu zúčtování na dosažení protiodchylky za účelem zisku je unikátní v České Republice, neboť ve většině okolních států není tato spekulace povolena.

Pro dosažení zisku je nutné predikovat průměrnou hodinovou hodnotu systémové odchylky s co největší přesností. Cílem této práce je tedy návrh modelu, který doporučí optimalizaci protiodchylky subjektu zúčtování. Je zde mnoho faktorů, které ovlivňují systémovou odchylku a způsobují její náhlé skokové změny. S těmito faktory není obecně ve stávající literatuře počítáno, což snižuje přesnost predikce. V mé práci do predikčního modelu zahrnu mnoho vstupních proměnných, které tyto změny systémové odchylky dokážou vysvětlit a tedy i predikovat. Vstupní proměnné budou použity jak v jejich hodnotovém vyjádření, tak ve formě rozdílových hodnot. Tyto rozdílové hodnoty budou vypočítány jako rozdíl sousedních hodnot nebo rozdíl mezi plánovanou a skutečně naměřenou hodnotou.

Predikci systémové odchylky není nutné provádět v její přesné hodnotě, jelikož tato hodnota není potřebná pro optimalizaci protiodchylky subjektu zúčtování. Pro snížení rizika vycházejícího ze spekulace a optimalizaci výnosů z protiodchylky definuji intervaly systémové odchylky, které budou mým modelem predikovány. Hranice těchto intervalů musí být vhodně zvoleny, abychom využili všechny informace, které vstupní proměnné mohou přinést. Pro vyhodnocení optimalizace vyčíslím hodnotu zisku nebo ztráty plynoucí ze spekulace. Ze spekulace rovněž vyvstávají náklady ušlé příležitosti, které musíme brát v potaz, neboť tyto náklady mohou převážit výnosy plynoucí ze spekulace. Náklady ušlé příležitosti vznikají z nutnosti ponechat si spekulativní rezervu pro možnou optimalizaci protiodchylky. Výsledky plynoucí z optimalizace protiodchylky subjektu zúčtování, predikované navrženým modelem, porovnáme s široce rozšířeným a akademicky používaným ARMA modelem, který je naším navrženým modelem výrazně překonán.

Klíčová slova:

Systémová odchylka, subjekt zúčtování, vstupní proměnné, intervalová distribuce, predikce

List of terms and abbreviations:

ARMA = autoregressive–moving-average model

BMP = balancing market price

BMP- = balancing market price (downward)

BMP+ = balancing market price (upward)

BRP = balance responsible party

BRP imbalance = difference between supply and demand of the BRP portfolio

Direction accuracy = percentage of successfully forecasted direction of imbalances

Downward regulation energy = negative regulation energy traded on the balancing market

Export-import diff = difference between planned and actual measured difference between export and import

Export-import real = actual measured difference between export and import

IMP = intraday electricity market price

Interval accuracy = percentage of successfully forecasted intervals

Photovoltaic CZ diff = difference between planned and actual measured photovoltaic generation CZ

Photovoltaic CZ real. = actual measured photovoltaic generation CZ

Photovoltaic DE diff = difference between planned and actual measured photovoltaic generation DE

Photovoltaic DE real. = actual measured photovoltaic generation DE

PR = primary regulation (part of ancillary services)

RES = renewable energy sources

SDAP = spot day-ahead electricity market price

SR = secondary regulation (part of ancillary services)

System imbalance = difference between supply and demand

Total consumption – plan = day-ahead forecast of the total consumption in the CZ

Total consumption - plan change = step change of the day-ahead forecast of the total consumption in the CZ

Total consumption - plan minus real = difference between planned and actual measured day-ahead forecast of the total consumption in the CZ

Total consumption – real = total consumption in the Czech Republic

Total consumption change = step change of the total consumption in the Czech Republic

Total supply – plan = day-ahead forecast of the total supply in the CZ

Total supply - plan change = step change of the day-ahead forecast of the total supply in the CZ

Total supply - plan minus real = difference between planned and actual measured day-ahead forecast of the total supply in the CZ

Total supply change = step change of the total supply in the Czech Republic

Total supply real. = total supply in the Czech Republic

TR = tertiary regulation (part of ancillary services)

Upward regulation energy = positive regulation energy traded on the balancing market

Wind DE change = step change of the actual measured wind generation DE

Wind DE diff = difference between planned and actual measured wind generation DE

Wind DE real. = actual measured wind generation DE

Obsah

List of Tables:

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Publications related to the dissertation thesis:

Impact publication:

Michael Frömmel, Xing Han, Stepan Kratochvil, Modeling the daily electricity price volatility with realized measures, Energy Economics, Volume 44, July 2014, Pages 492-502, ISSN 0140-9883, http://dx.doi.org/10.1016/j.eneco.2014.03.001.

(http://www.sciencedirect.com/science/article/pii/S0140988314000425)

Keywords: Volatility forecasting; Intraday range; Realized GARCH; Electricity

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Kratochvíl, Š. - Starý, O.: PREDICTING THE PRICES OF ELECTRICITY DERIVATIVES ON THE ENERGY EXCHANGE. Acta Oeconomica Pragensia. 2013, vol. 6, no. 6, art. no. 4, p. 65-81. ISSN 0572-3043.

Authorship: 50 %

KRATOCHVÍL, Š. and J. BEJBL. Analýza systémové odchylky. Energetika. 2015, 65(1/2015), 10-13. ISSN 0375-8842.

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Authorship: 50 %

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Authorship: 50 %

Other publications:

KRATOCHVÍL, Š. and J. BEJBL. Analysis of the patterns at the system imbalance. In: POSTER 2014 - 18th International Student Conference on Electrical Engineering, 2014-05-15. Prague: Czech Technical University, 2014, ISBN 978-80-01-05499-4.

Authorship: 50 %

KRATOCHVÍL, Š. and J. BEJBL. The system imbalance prediction. In: Poster 2015. Poster 2015, Praha, 2015-05-14. Praha: České vysoké učení technické v Praze, 2015, ISBN 978-80-01-05728-5.

Authorship: 50 %

KRATOCHVÍL, Š. and J. BEJBL. Analysis and the methods of forecasting of the intra-hour system imbalance. In: Poster 2016. Poster 2016, Praha, 2016-05-24. Praha: České vysoké učení technické v Praze, 2016, ISBN 978-80-01-05950-0.

Authorship: 50 %

All the Poster publications were awarded by the first place among the presented papers.

1. Introduction

Every trader, generator, operator or generally power market participant has several opportunities how to act (make profit) on the electricity market. There are long-term strategies such as futures or forwards contracts enabling selling or buying electricity under annual, monthly and weekly contracts[1]. In addition to them, there are short-term strategies, which consist mainly in the day-ahead market serving to close the position in the sense of balancing the portfolio to cover all the customers' needs and consume all the electricity from the suppliers[2]. Another market in short-term strategies is the intraday market for speculations on the price deviation and compensation of the deviations caused by the change in expected supply and consumption of the electricity. The last part is the balancing market organized by the TSO (transmission system operator) for buying upward and downward regulation energy for the balancing system demand and consumption in the real time.

The balancing market is operated by the TSO, which is responsible for balancing electricity supply and demand in real time for the entire electricity network. This amount of energy is referred to as system imbalance and is created by the summation of the system imbalances of all the balance responsible parties (BRP). A BRP is a market participant that has taken the responsibility for balancing the portfolio of generation and consumption. BRPs are obliged to submit their energy program on the day before the day of the delivery and are penalized for each deviation from this plan. This so-called imbalance settlement process gives BRPs an incentive to balance their portfolio with the highest precision. This part of the energy market is not so important for most of the BRP, but there is a huge opportunity to hedge the trader's portfolio or optimize the BRP imbalance in order to gain profit.

In this dissertation I focus on the possibilities how to act on this part of the energy market. To optimize the BRP imbalances, there is a need to forecast the average system imbalance value with the highest prediction as the optimization deals with the achieving BRP imbalance in the opposite direction to the system imbalance.

The forecast of the system imbalance is not needed in the point forecast as concrete value of the system imbalance is not necessary for the optimization of the BRP imbalance. Therefore, I

[1] For CWE (central western Europe) see https://www.eex.com/en/ for Czech market see https://www.pxe.cz/

[2] For CWE (central western Europe) see https://www.epexspot.com/en/ for Czech market see http://www.ote-cr.cz/

define the intervals of the system imbalance, for which is the forecast made. The multiple inputs describing the energy market and creating the system imbalance are used in the interval forecast. I calculate the profit and loss resulting from the optimization, to evaluate the BRP imbalance optimization,

The results of the dissertation thesis are associated with the long-term research. Parts of this research have already been published on the conferences and in the literature. [38, 39, 40, 41, 48, 49, 50, 51]

2. Process and methodology of the work

In this chapter, the process of the whole study and then the methodology of the scientific work is described.

2.1. The process of the forecast methodology and its preparation

The background for the study is detail research of the literature on this topic. This research should be done not only in the market of Czech Republic, but also surrounding energy markets, because of the interconnections between European markets. Research can be seen in the chapter 4 called *State of Art*.

For the successful forecast of the system imbalance I need to define the right inputs able to increase the accuracy of the forecast model of the system imbalance. These inputs are exogenous variables defining and creating the system imbalance. For achieving this goal I process as follows:

1. I define the theoretical current imbalance pricing mechanisms. (chapter 5.2.)
2. I present the concrete imbalance pricing mechanisms at the surrounding or important European markets, which give us the relations of the system imbalance value, the value of the balance responsible party's imbalance and the spot price. Also the relation of the price for the balance responsible party's imbalance in order to the direction of the system imbalance shows us the potential of the forecast. (chapter 5.3. and the subchapters)
3. Next I aim on the market of the Czech Republic as this market is primary objective of my research. The definition of the system imbalance in the Czech Republic legislation and the methodology of the pricing of the balance responsible party's imbalances is defined in the chapter 5.4. There is pointed out the relation of the direction of the system imbalance to the direction of the BRP's imbalance and the importance of the speculation given by the historical development of these values. For the forecast I need to define the deterministic part of the system imbalance data, which is caused by its seasonality and the autocorrelation (chapter 6.2.). The seasonality of the data was not found significant and the autocorrelation show only short memory of the process (just a few last hours).
4. Next I aim on the forecast of the intra-hour system imbalance trend. I base the model on the three pillars.
    a. Conflict between hourly level of the supply from the classical energy sources (mainly coal and nuclear power plants) and minute data of the demand.
    b. Variable production of the renewable energy sources.
    c. Trader's speculation influencing the intra-hour trend of the system imbalance.

Not each of these pillars improves the final forecast, so the model consists of the pillars, which are relevant. Despite the fact, that sufficient relation was not found between hourly value of the system imbalance and the intra-hour trend of the system imbalance and therefore the intra-hour trend cannot be used for the system imbalance forecast, the importance for market participants was showed on the critical situation on September 2015 in Czech Republic. See chapter 7.

5. Based on the methodology of the pricing of the BRP's imbalance, I define the basic exogenous variables influencing and creating the system imbalance. These exogenous variables can be divided into three classes (chapter 8.):
    a. Demand variables
    b. Supply variables
    c. Variables capturing market participant's behaviour
6. Using only the pure value of the exogenous variables leads to the loss of the information. Therefore I calculate other exogenous variables from the current ones as the difference between two exogenous variables and the difference between neighbour values of the one exogenous variable.

After defining the exogenous variables I need to modify the data used in the model and sort them.

1. I need to clean the data sets from the irrelevant samples (for example night hours of the data of photovoltaic production).
2. For the successful forecast of the system imbalance is not needed, the exact value of the system imbalance, but mainly its direction and the interval of it. For this reason I define the intervals of the system imbalance and calculate the corresponding intervals for each exogenous variable. (chapter 9.1.)

Having distributed all input data into intervals, I define the forecasting model and evaluate the forecast.

1. I define the forecasting model as the sum of the weighted, intervals distributed exogenous variables. The model output is the forecasted interval of the system imbalance. (chapter 9.2.). Also the benchmark model is presented in chapter 9.3. This model is presented in order to evaluate the suggested forecast model of the system imbalance.

2. The forecasted interval is connected with the speculation amount of the balance responsible party imbalance. This makes the business position of the balance responsible party which is evaluated in order to calculate the profit or loss from the speculation.
3. The results are the profit and loss from both in-sample and out-of-sample speculations. (chapters 10.1. and 10.2.). The results of the proposed model are compared with the benchmark ARMA model.

The whole process is presented in Figure 1.

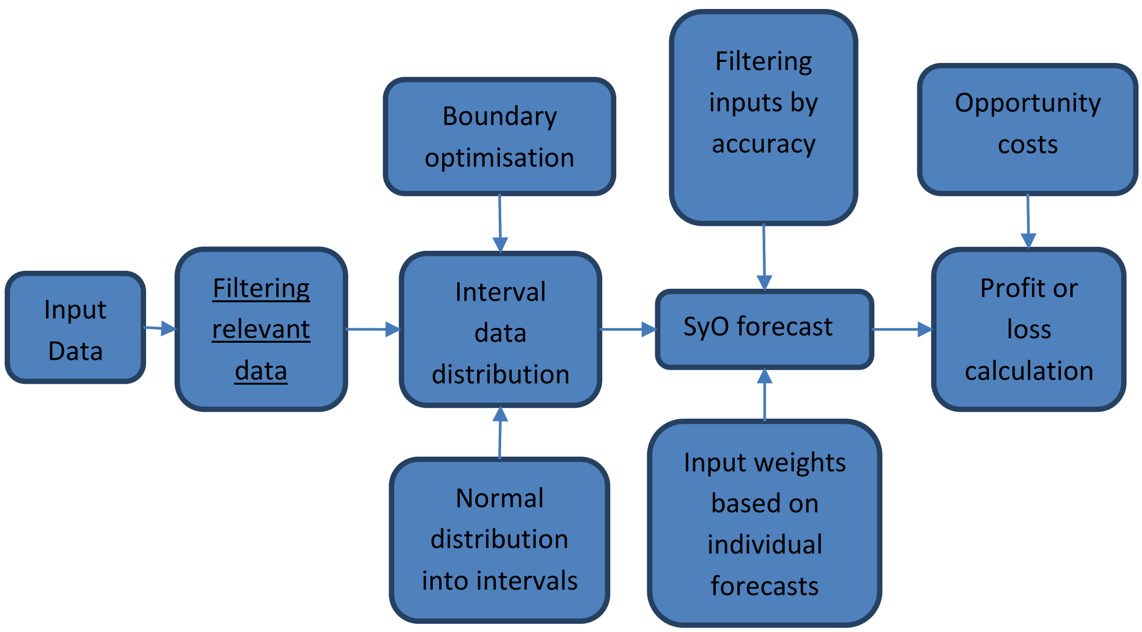

Figure 1 The entire process diagram. Source: own calculation.

2.2. Methodology of the work

The first step is the **research in the technical and economical literature, journal articles and legislation in the energy market areas** in the important European energy market sectors (included Czech Republic) to identify the methods and input variables applicable for the system imbalance forecast.

Then I analyse the state of art methods and input variables for the system imbalance forecast. These methodologies and input data are inadequate to describe the present state in the energy sector, which changed in the last year by the increase of the intermittent energy sources.

Next I realize the **empirical survey**. It is **explorative research** for the description of the events. So I apply the **descriptive approach**.

Exploratory research *"seeks, and describes how the system behaves, and what its relations are. It is performed in order to obtain a better understanding of what is happening and why it is happening. The basis is the description and classification of the problem."* Exploratory research is made in order to determine hypotheses.

Exploratory research in the thesis is made on the system imbalance pricing mechanisms, where key elements influencing the system imbalance are determined.

Descriptive approach - "*It is based on an empirical analysis of existing and underlying systems and shows how it really is.*" The method is **empirical research**. By this approach I analyse the Czech energy market and its unique parameters given by the possibility of the speculation of the BRP to achieve the different direction of the BRP imbalance to the system imbalance. By this I define the set of the exogenous input variables usable for the system imbalance forecast.

Then I apply the **inductive approach**. This approach is based on the evaluation of the achieved input data. "*Collected data is used to provide several different perspectives on the problem. Based on the findings, the hypotheses are generated and subsequently tested.*"

The data are analysed by the **correlation and auto-correlation analyses** in order to find out relations among data sets. After filtration of the data sets, eliminating the irrelevant data, the data sets are distributed into intervals to increase the accuracy of forecast of the interval of system imbalance, which is needed for the speculation purposes.

The aim is to limit the number of used exogenous input variables in order to decrease the time of the model evaluation and make it more transparent for the user. I can therefore talk about **abstraction**. By abstraction I focus only on the objects intrinsic characteristics or features, whose exploration can find answers to questions.

By **synthesis** of all knowledge's (weighted, filtered and distributed input variables) is set the forecasted model that's output is the forecasted interval of the system imbalance. Output result leads to the recommendation of the BRP imbalance speculation, which is financially evaluated in order to calculate profit or loss from the speculation. This model is therefore generally applicable by all market participants with its own sources of electricity production.

3. Goals and hypothesis of the thesis

The main goal of the dissertation thesis is *to forecast system imbalance in order to achieve profit from having opposite BRP's imbalance to the system imbalance*. It is not needed to forecast the exact value of the system imbalance to meet this goal. It is sufficient to forecast an interval, in which the system imbalance is. So in the dissertation work both the interval data (interval forecast) and two sided forecast (2 intervals) are studied to gain the profit.

The partial goal is *to analyse, if there is the connection between Germany market indicators and the Czech Republic market indicators*. Share of the RES power generation is much higher in Germany compared to the Czech Republic. As these sources are mostly intermittent and weather dependent [42], change in the production affects the system imbalance very significantly. The location of the market areas, liquidity of trades and other aspects result in very strong correlation of the German and the Czech power market prices (the Czech power market is influenced by the German power market). The hypothesis of the dissertation thesis is the fact that the German RES power generations influence the Czech system imbalance. This is a very important question, which could lead to an increase of the accuracy of the Czech system imbalance forecast.

Hypothesis for the dissertation are therefore following:

1. System imbalance value can be forecasted with sufficient accuracy to gain the profit speculating on the opposite position of the BRP imbalance

1.1 System imbalance value can be forecasted with sufficient accuracy to gain the profit speculating on the opposite poInputs described in this dissertation are relevant for the system imbalance forecast and their usage in the forecasting methodology improve the accuracy of the final system imbalance forecast. of the BRP imbalance

2. Interval forecast can lead to better prediction than two-sided interval. Hypothesis is based on the assumption that the two-sided forecast cannot reduce the risk of the changing the direction of the system imbalance by the BRP's imbalance speculation. Interval forecast can also increase the profit by changing speculation level (BRP's imbalance value) among the intervals.

3. The intra-hour trend of the system imbalance is a relevant input for the hourly system imbalance forecast. There is a relation between the intra-hour trend of the system imbalance and hourly system imbalance.

4. Logical relation between German and Czech power markets exists. Quickly increasing share of RES power generation affects the Czech system imbalance.

4. State-of-Art

Three main pillars of the balancing market can be defined. These are balance planning, balancing service provision and imbalance settlement [8]. Balance planning involves the submission of energy schedules by the BRPs to the TSO. Balancing services are provided by the market participants and their activation serves for the restoration of the system balance. Balance settlement is a type of financial settlement of schedule deviations of the BRPs to the TSO. Different balance settlements have different imbalance prices, which are paid or received, while the BRPs deviate from the scheduled values.

Van der Veen [6] defined six basic imbalance pricing mechanisms used in Europe. These are the single pricing used in Spain and Greece, with a marginal regulation price for both long and short imbalance prices. Another is the dual pricing applied in the Netherlands, which differentiates between upward and downward regulation prices in two-sided regulation. The third is the two-price settlement used in the Nordic region, where different prices are applied to BRPs, whose imbalances are in the direction of the system imbalances and the opposite, respectively. Another is the additive component system, where an additive component is added to the imbalance price when a security-related criterion is met. The fifth is the imbalance pricing based on total costs used in Germany [9, 15], where the imbalance price is not based on the marginal regulation price, but is defined on the basis of the total costs. The last one is the alternative payment direction used in the Czech Republic, where BRP receive money from the TSO when the direction of their imbalance is the opposite of the system imbalance. All the pricing mechanisms are described in detail in Chapter 5.2. These pricing mechanisms differ significantly and the BRP’s decisions should be modified according to the pricing mechanism used by the TSO.

Whereas papers on modelling of long-term and short-term markets (day-ahead or intraday) are numerous, significantly less attention is paid to the balancing market and the system imbalances especially in relation to neighbouring markets.

Typical models describing long and short-term markets are as follows. Seifert and Homburg [1] present autoregressive (mean-reversion) and jump-diffusion time series models. This approach is modified by adding longer memory by Conejo [2] to ARX or ARMAX models. Another branch of models is presented by Weron [3]. This model is called a regime-switching model and uses Markov processes to switch between different states to model electricity price jumps [50]. Another way of forecast can be made in the terms of volatility of the spot price [48].

As stated above, there are not so many papers concerning balancing markets. There are two main groups of papers. The first are papers describing the balancing market (e.g., [24]). Koliou et al. [10] describe Germany's power market and the influences of RES (renewable energy resources) power generation on the system imbalance, which can be balanced by the demand-side flexibility. Van der Veen et al. [6, 7] study the imbalance settlement in Northern Europe and their influences on the BRP market behaviour and system imbalance. They conclude that different imbalance settlements lead to different costs for the BRP, but despite these differences the BRPs are advised to keep a small and positive imbalance as it leads to lowest imbalance costs. Haring [16] proposes an imbalance settlement procedure with an incentive-compatible cost allocation scheme which should keep imbalances close to zero. Mielczarski et al. [19] argue that balancing energy in Poland is cheap because of the supply part of electricity demand via the systems reserve capacity. Kirschen and Garcia [20] find the reason for expensive balancing energy in England to be due to market participants' keeping capacity reserves.

Another group is papers on forecasting of system imbalance prices. Olsson et al. [5] model the real-time balancing power market price using a combination of the SARIMA model describing seasonal behaviour and the autocorrelation of time series of system imbalance prices and the Markov processes modelling the changing of states between upward and downward regulation. The SARIMA model prediction is described in Möller [18]. Another approach, presented by Brolin et al. [4], is forecasting of the balancing power price using a nonlinear time series model. The model reflects real-time markets applying hourly marginal prices, different for upward and downward balancing. Furthermore, the model is aimed at Monte Carlo simulation and generation of scenario trees. An extension of the model consists in using exogenous variables, where hourly day-ahead spot prices and real-time balancing demand are used as exogenous variables. Garcia et al. [12] forecast system imbalance by using exogenous variables describing supply and demand using data mining techniques, an ARIMA model and neural networks. Klaeboe [11] offers a benchmark of models for balancing states, where hour-specific Markov, duration-dependent Markov and arrival rate models are presented. Other models are benchmarked for balancing volume forecasting, namely the RAND, HIST, SARMA and CROST models. The final benchmarking is made for balancing premium forecasting, where ARMA, ARX, ARM, EXO and NAIVE models are benchmarked. For more information, see Klaeboe [11].

All these approaches have a lack in insufficient numbers of exogenous variables. Mainly due to the growth of RES, the share of which is aiming to reach 20% by the 2020, the balance responsibility of the BRPs is increasing since these sources are intermittent. RES in electricity are very hard to forecast and, as per Directive 2009/28/EC, RES generators receive priority access to the electricity grid, which leads to higher system imbalance occurrence. In my opinion, these RES power generation variables and the difference between forecast and actually produced amounts of energy should be incorporated in the model for increasing the accuracy of the forecast of the system imbalance.

The development in the field of energy sources led in the past years to the increasing share of the RES in power generation, mainly PV (photovoltaic). This led to the decreasing of the price for the electricity power, and increasing the price for the electricity for the customer (all because of subsidy) [43]. It is a question, how far can this trend go and what should be the changes in the subsidy system to handle this problematic of the future increase of the share of the RES in power generation. [44]

Nowadays, the RES in power generation makes the huge problems in the electricity transmission in the central Europe. This is caused by the difference between the place of the generation of the electricity and the place of the consumption. These problems can be best visible in the Germany, where huge generation of the wind power plants is on the north and the consumption on the central-south of the country. Unconsumed electricity is also transported to the south east of the Europe, which use all enable boarder-transmission capacity and can cause the future problems. [45]

Some states try to prevent these cross-border flows by building the Phase-shifting transformers [46]. These devices enable to control the cross-border flow and stop the critical amount of the electricity to flow into the state transmission system. However, this solution only transfers the problem into the country with the extreme RES power generation with insufficient transmission capacity.

All these aspects have to be held in the thesis and all the facts has to be incorporated into the suggested methodology of the forecast.

Dissertation work differs significantly from the approaches mentioned above. In my case study, I use data from the power markets of the Czech Republic and Germany, but it is internationally portable and there are no limits on using it anywhere. The Czech market is different in the ability of the BRPs to speculate on the system imbalance, where the BRP imbalances that are opposite to system imbalance lead to receiving money from the TSO and the same direction of the imbalances leads to payments to the TSO. This means that BRPs are paid, when they help the system (by decreasing the system imbalance) and are penalized when they increase the system imbalance. This system is quite unique in Europe and most of the TSOs do not use this price settlement design. Thus, the aim of the thesis is to develop the methodology to minimize the imbalance costs (as other papers do) but to maximize the profit from the BRP imbalances. The approach to handling the data is different from others, with respect to the aim of the dissertation. I do not forecast the system imbalances as a time series, but divide these data into several intervals, which are further forecasted. The speculations intervals are sufficient for my optimization as I need to determine the speculative amount of the BRPs' imbalance.

Another difference is in the use of exogenous variables. I use multiple inputs describing the deviations in the planned supply and the behaviour of other BRPs. Inputs describing the deviations in supply are aimed at RES, specifically wind and PV power plants (in the Czech Republic and in Germany). Inputs describing the BRP behaviour are day-ahead prices, intraday prices and balancing energy bought by the TSO. All the inputs are described in detail in Chapter 8.

The rest of the dissertation is organized as follows. The fifth chapter presents the methodologies of imbalance pricing mechanisms for European markets, which are defined in the next chapter for the Czech Republic's power market with statistical analysis of the system imbalance. In chapter seven is presented the model for intra-hour trend of the system imbalance forecast and the relation with the hourly system imbalance. Chapter eight defines the possible inputs that may be used as exogenous variables for the system imbalance forecast. In the chapter nine is presented the methodology of interval data distribution and description of the forecasted model. Chapter ten describes the results of the case study (in-sample and out-of-sample forecast). The eleventh chapter evaluates the hypothesis set in the chapter three. The last, twelfth chapter summarizes the conclusions.

5. System imbalance definition

At first, I define BRP imbalance. BRP imbalance is the difference between the scheduled value of energy supplied into the grid and the actual supply, or the difference between the scheduled value of demand and actual demand, respectively. Supply is marked by the positive sign and demand by the negative. For each PTU (programme time unit), the imbalance is set by the market operator. BRP imbalance can be defined according to [13] as:

$$IM_{BRP} = E_{BRP}^{sch} - E_{BRP}^{act} \tag{1}$$

Where:

IM_{BRP} is the BRP imbalance;

E_{BRP}^{sch} is the scheduled supply or demand energy;

E_{BRP}^{acc} is the actual supply or demand energy.

System imbalance is commonly defined as the sum of the BRP imbalances, but this is not accurate. To define system imbalance, I need to modify the BRP imbalance equation by adding import and export variables, since these variables are considered while calculating system imbalance, loss in the transmission network and regulation energy. The next methodology can be defined as:

$$SI = \sum_{\forall BRP} IM_{BRP}$$
$$SI = \sum_{\forall BRP} E_{BRPH,S}^{act} + E_{BRPF,I}^{act} - (E_{BRPH,D}^{act} + E_{BRPF,E}^{act} + E_{L}^{act}) - (E_{BRPH}^{sch} + E_{BRPH,RE}^{sch}) \tag{2}$$

Where:

SI is the system imbalance;

$E_{BRPH,S}^{act}$ is the domestic BRP's actual supply;

$E_{BRPF,I}^{act}$ is the foreign BRP's actual import;

$E_{BRPH,D}^{sch}$ is the domestic BRP's actual demand;

$E_{BRPF,E}^{act}$ is the foreign BRP's actual export;

E_L^{act} is the actual loss in the transmission network;

E_{BRPH}^{sch} is the domestic BRP's scheduled demand or supply realization diagram (hourly values of the supply or demand respectively); and

$E_{BRPH,RE}^{sch}$ is the domestic BRP's value of the regulation energy.

This methodology covers all the areas of the system imbalance and sets the value for the each PTU.

Czech Legislative framework for the evaluation and pricing of the imbalances are made by following norms:

- *Law 458/2000 Col., energy law*[3], which defines the basic terminology and determinates the rights and obligations in the system of the imbalances settlement
- *ERU Decree 408/2015 Col. on Electricity Market Rules*[4], where the basic principles of the system imbalances settlement are set.
- *Price decisions of the Energy Regulatory Office*[5], which set the prices of the regulated services connected with the delivering of the electricity. In these decisions, there are set the input parameters for the pricing imbalances as the minimum system imbalance price etc.
- *Terms of OTE, a.s. for energy market*[6], where the technical details are set, for example the way of communication during sending the data, setting financial clearing, reclamations etc.

5.1. Balance responsible party (BRP)

According the energy law, the electricity market participants are the producers of the electricity, transmission system operator (TSO), distribution system operators, electricity market operator (OTE a.s.) and the electricity traders (or the customers, who consumes the electricity from

[3] *Zákon 458/2000 Sb., energetický zákon*

[4] *Vyhláška 408/2015 Sb. O Pravidlech trhu s elektřinou*

[5] *Cenové rozhodnutí Energetického regulačního úřadu* (ERÚ)

[6] *Obchodní podmínky OTE, a.s. pro energetiku*

another trader or producer). All market participants have the obligation to be registered at the electricity market operator. Being registered, they became the “registered electricity market participants”.

There is a lot of the electricity market participants and it is not practical (probably neither technically handled) to make the imbalance settlement for each market participant. Here is therefore defined the balance responsible party (BRP), who has the contract about the BRP imbalance settlement with the electricity market participant and has the financial responsibility for its imbalance (one of the conditions is the adequate financial clearing). Electricity market participant, who is not the BRP, has to transfer the responsibility for his imbalance to some BRP. By this contract - supply, demand and his trading position are included into the balance position of the BRP. BRP therefore represents the balancing group made by the BRP and registered market participants, for which BRP take over the responsibility for the imbalance.

BRP has the following rights (after fulfilment of the conditions):

- To trade on the organized energy markets
- To register bilateral trades (OTC) with another BRP
- To participate in the cross-boarding trading
- To provide regulation energy

BRP has the following obligations:

- To provide actual data for the financial settlement of the imbalance
- To make a payment for the BRP imbalance

5.2. Imbalance pricing mechanisms

Specification of the imbalance pricing mechanism is not only important for the market participants in the country in which they exist, but also for participants that have access to the country’s energy exchange. Due to the liberalization process and connection of neighboring market areas, it is possible to trade in other counties and if it is not allowed to speculate on the system imbalance occurrence in a market participant’s country, it can do speculation by holding an open position in the country where the speculation is allowed. This increases interest in countries, which would not be too interesting otherwise, such as the Czech Republic. This country has a rather small power exchange with not so many participants and small liquidity of the market. But for participants, primarily operating in Germany (for example), this location could be very interesting as in Germany it is not allowed to speculate on the profit from different directions of BRP imbalance and system imbalance whereas this is possible in the Czech Republic; see [23].

Next I present six different imbalance pricing mechanisms defined by Van der Veen [6] used in Europe. The term “short imbalance price” means surplus in consumption or shortage of supply of the BRP; “long imbalance price” refers to the opposite.

1) Single pricing

This is the simplest way to calculate system imbalance prices. Both short and long imbalance prices are set as the marginal regulation price in the main regulation direction. The main regulation direction means that for upward regulation the system is in a shortage and has a negative system imbalance. The situation is opposite for downward regulation.

2) Dual pricing

This mechanism extends the previous one by adding the pricing methodology for two-sided regulation (the case, where both upward and downward regulation is activated). In this situation, the short imbalance price is the upward regulation price and the long imbalance price is the downward regulation price.

3) Two-price settlement

This mechanism differs significantly from the above ones. In this mechanism, the prices for the direction of the BRP imbalance and system imbalance are different. If the BRP imbalance is in the same direction as the system imbalance, its price is based on the marginal regulation price. However, if the direction is opposite, the price equals the day-ahead market price. In this mechanism, the BRP, who helps to balance the system imbalance (lower the system imbalance), is paid the day-ahead price, which can be regarded as the selling of the regulation energy.

4) Additive component

This settlement pricing mechanism serves as a supplement to the one above and has the system-security function. When the security-related criterion threshold is met, the additive component is applied and increases the price for the BRP imbalance. This component is added to the short imbalance price and subtracted from the long imbalance price.

5) Pricing based on total costs

This pricing mechanism calculates both short and long imbalance price as the sum of the balancing costs divided by the activated regulation volume. There can be some limits equal to marginal upward and downward regulation.

6) Alternative payment direction

This mechanism is the most important for us, because of my use of imbalance data for the Czech Republic, where imbalances are priced using the alternative payment direction mechanism. The normal situation common for all the above mechanisms is that BRPs pay when they are short and receive money for being long. This particular mechanism tries to force the BRPs to help lower the system imbalances. BRPs are paid when their imbalance is opposite to the system imbalance (no matter if their position is long or short) and pay the imbalance price for BRP imbalance in the same direction as the system imbalance. It can be said that BRPs helping the system are rewarded while BRPs increasing the system imbalance (unbalancing the system) pay for the imbalance.

5.3. System imbalance pricing in selected European countries

In this chapter are described methods of the pricing system imbalance in the selected European countries. The pricing mechanism is introduced for the following countries:

1. Slovakia
2. Hungary
3. Germany
4. France
5. Great Britain
6. Switzerland
7. Belgium

In the following subchapter are used some term like PTU (program time unit), what is the period, which is the imbalances priced for and RE (regulation energy), which is the energy needed to balance the supply and demand. Here I use upward (increasing of the supply) and downward (decreasing of the supply) regulation energy.

5.3.1. Slovakia

Transmission system operator (TSO) in Slovakia is the SEPS, a.s. and the pricing of the system imbalance is made by the OKTE which is owned by SEPS, a.s. Energy market regulator is the ÚRSO, which issue the price decisions. PTU in Slovakia is 15 minutes.

The payment of the BRP consists of the payment for the BRP imbalance, payment for the procedure of pricing of the system imbalance, payment for the access into the system of imbalances settlement and the payment for the RE (regulation energy) according [28].

The payment for the procedure of pricing of the system imbalance is according [35] set on 0.0129 EUR/MWh. The payment for the access into the system of imbalances settlement is made once a year and is set on 14683 EUR [35].

The quotient for payment for the RE and the payment of the BRP for the RE are calculated as follows:

$$pN_{RE} = \frac{N_{RE}}{CO} \tag{3}$$

$$PRE_{SZi} = pN_{RE} * (COC_{SZi} + CDC_{SZi}) \tag{4}$$

Where pN_{RE} is the quotient for the payment for the RE, N_{RE} is the total costs for the RE and CO is the amount of the RE. PRE_{SZi} is the payment of the BRP from the total RE, COC_{SZi} is the total demand of the BRP, CDC_{SZi} is the total supply of the BRP and *i* is the index of the BRP.

The payment for the BRP imbalance differs while the BRP imbalance is in the opposite or same direction to the system imbalance.

$$Payment_{same\_direction} = IM_{BRP} * IP \tag{5}$$

$$Payment_{opposite\_direction} = IM_{BRP} * IP * kzpo \tag{6}$$

Where IM_{BRP} is the BRP imbalance, IP is the imbalance price and $kzpo$ is the coefficient set by [33].

Table 1 BRM imbalance price settlement in Slovakia. Source [28].

	Positive system imbalance	Negative system imbalance
Positive BRP imbalance	MP_{RE-}	$MP_{RE+} * kzpo$
Negative BRP imbalance	$MP_{RE-} * kzpo$	MP_{RE+}

Imbalance price is defined in the Table 1, where MP_{RE-} is the minimum activated RE price and MP_{RE+} is the maximum price of the activated RE.

5.3.2. Hungary

Transmission system operator (TSO) in Hungary is the MAVIR and the pricing of the system imbalance is made by the HUPX Energy market regulator is "The Hungarian Energy and Public Utility Regulatory Authority", which issue the price decisions.

Hungary imbalance pricing mechanism is derived from the method used in Belgium.

Here I need to differentiate the imbalance pricing methods into 4 cases:

For the case with negative system imbalance and negative BRP imbalance I calculate the IP (imbalance price) as following:

$$IP = (1 + b) * MAX[P_{RE+}; P_{SPOT}] \tag{7}$$

Where b is the "Belgian charge", which is according [34] 12%, P_{RE+} is the weighted price of the upward regulation energy and P_{SPOT} is the spot price for the evaluated hour.

For the case with negative system imbalance and positive BRP imbalance I calculate the IP as following:

$$IP = (1 - b) * (-1) * P_{SPOT} \tag{8}$$

For the case with positive both system imbalance and BRP imbalance I calculate the IP as following:

$$IP = (1 - b) * MAX[P_{RE-}; P_{SPOT}] \tag{9}$$

Where P_{RE-} is the weighted price of the downward regulation energy. In the situation, where the P_{RE-} is negative, the equation changes as follows:

$$IP = (1 + b) * MAX[P_{RE-}; (-1) * P_{SPOT}] \tag{10}$$

For the last case of positive system imbalance and negative BRP imbalance I calculate the IP as following:

$$IP = (1 + b) * P_{SPOT} \tag{11}$$

For the penalization of the significant BRP imbalances are defined two values. At first it is the level of the number of imbalances tolerance "n", which is on the level of 3,5% and the value of imbalance "s", which is the value of 25% from the system imbalance [34].

Penalization is applied to the BRP, who has its imbalance in the same direction to the system imbalance and therefore increase the system imbalance. So for the both negative system and BRP imbalance, the imbalance pricing mechanism is as followed:

$$IP = (1 + b) * MAX[P_{RE+}; P_{SPOT}] * (1 + s) \tag{12}$$

For the both positive system and BRP imbalance, the imbalance pricing mechanism is as followed:

$$IP = (1-b) * MAX[P_{RE-}; P_{SPOT}] * (1+s) \tag{13}$$

And for the negative P_{RE-}:

$$IP = (1+b) * MAX[P_{RE-}; (-1) * P_{SPOT}] * (1+s) \tag{14}$$

5.3.3. Germany

In Germany, there are four Transmission system operators (TSOs). These are the Amprion, Tennet, 50 Hertz Transmission and TransnetBW. Energy market regulator is the "Bundesnetzagentur", which issues the price decisions. PTU in Germany is the 15 minutes.

The imbalance pricing mechanism consists of four sequential steps [27].

At first step, the IP is set as following:

$$IP_1 = \frac{\sum costs - \sum revenues}{saldo} \tag{15}$$

Where:

$\sum costs$ is the sum of total cost

$\sum revenues$ is the sum of total revenues for the activated regulation energy.

The $saldo$ is the difference between amount of activated upward and downward regulation energy.

For elimination of the extreme imbalance prices, there is the lower and upper threshold of the highest and lowest price of the activated regulation energy.

If $IP_1 \leq 0$ then:

$$IP_2 = MIN[|IP_1|; |MP_{REMAX}|] \tag{16}$$

If $IP_1 > 0$ then:

$$IP_2 = (-1) * MIN[|IP_1|; |MP_{REMAX}|] \tag{17}$$

Where $|MP_{REMAX}|$ is the absolute value of the maximal price of the activated regulation energy.

In the third step is IP_2 compared with the price average weighted intraday price on EPEXSpot.

If the $saldo$ is positive:

$$IP_3 = MIN[P_{WSPOT}; IP_2] \tag{18}$$

If the $saldo$ is negative:

$$IP_3 = MAX[P_{WSPOT}; IP_2] \tag{19}$$

Where P_{WSPOT} is the average weighted intraday price on EPEXSpot.

In the final step, there are added or deducted penalty for the used more than 80% of the reserved regulation energy.

Three situations can happen:

1. $saldo > 0.8 * RE_+$

The formula for this situation is following:

$$IP_3 = MAX[P_{WSPOT}; IP_2] \tag{20}$$

There is added the 50% of the originIP_3, where minimum is 100 EUR/MWh.

2. $saldo < -0.8 * RE_-$

The formula for this situation is following:

$$IP_4 = IP_3 - MAX[100\ EUR/MWh; 0.5 * |IP_3|] \tag{21}$$

There is deducted the 50% of the originIP_3, where minimum is 100 EUR/MWh.

3. $-0.8 * RE_- \leq saldo \leq .,8 * RE_+$

$$IP_4 = IP_3 \tag{22}$$

5.3.4. France

Transmission system operator (TSO) in France is the RTE which also deals with the pricing of the system imbalance. Energy market regulator is the CRE, which issue the price decisions. PTU in France is 30 minutes.

The price for the BRP imbalance in the opposite direction to the system imbalance is the spot price of the electricity. For the BRP imbalance in the same direction to the system imbalance is the price derived by the weighted average of the activated regulation energy [29]. Concrete methods are presented further.

For the positive both system imbalance and the BRP imbalance is the method as follows:

$$IP = \frac{P_{WRE-}}{(1+K)} \tag{23}$$

Where P_{WRE-} is the weighted average of downward the activated regulation energy and *K* is the constant, which is now set on the value of 0,08.

For the negative both system imbalance and the BRP imbalance is the method as follows:

$$IP = P_{WRE+} * (1+K) \tag{24}$$

Where P_{WRE+} is the weighted average of upward the activated regulation energy.

For the case, where the activated regulation energy would be zero, the imbalance would be priced by the spot price.

5.3.5. Great Britain

Transmission system operators (TSOs) in Great Britain are the National Grid Electricity Transmission (England and Whales), Scottish Power Transmission Limited (south of the Scotland) and Scottish Hydro Electric Transmission (north of the Scotland). The pricing of the system imbalance is made by the Elexon. PTU in Great Britain is 30 minutes.

The price for the BRP imbalance in the opposite direction to the system imbalance is the price of the electricity which should be paid on the energy Exchange. For the BRP imbalance in the same direction to the system imbalance is the price derived by costs of the activated regulation energy [31, 32].

For the positive both system imbalance and the BRP imbalance is the method as follows:

$$IP_j = \frac{\sum_i \sum_n \sum_k ((V_{RE-})_{ij}^{kn} * (P_{RE-})_{ij}^{n} * L_{ij}) + \sum_m ((V_{ORE-})_j^m * (P_{ORE-})_{ij}^n)}{\sum_i \sum_n \sum_k ((V_{RE-})_{ij}^{kn} * L_{ij}) + \sum_m ((V_{ORE-})_j^m * (P_{SOR-})_j)} \tag{25}$$

Where ((V_{RE-} is the volume of all accepted offers of the downward regulation energy in MWh, *L* is the multiplier of the loss during the transmission, V_{ORE-} is the volume of the downward regulation energy gained out of the balancing mechanism in MWh, P_{ORE-} is the price of the downward regulation energy gained out of the balancing mechanism and P_{SOR-} is the price of the long-term contracts for providing the short-term operational reserves.

For the negative both system imbalance and the BRP imbalance is the method as follows:

$$IP_j = \frac{\sum_i \sum_n \sum_k ((V_{RE+})_{ij}^{kn} * (P_{RE+})_{ij}^{n} * L_{ij}) + \sum_m ((V_{ORE+})_j^m * (P_{ORE+})_{ij}^n)}{\sum_i \sum_n \sum_k ((V_{RE+})_{ij}^{kn} * L_{ij}) + \sum_m ((V_{ORE+})_j^m * (P_{SOR+})_j)} \tag{26}$$

Where ((V_{RE+} is the volume of all accepted offers of the upward regulation energy in MWh, *L* is the multiplier of the loss during the transmission, V_{ORE+} is the volume of the upward regulation energy gained out of the balancing mechanism in MWh, P_{ORE+} is the price of the upward regulation energy gained out of the balancing mechanism and P_{SOR+} is the price of the long-term contracts for providing the short-term operational reserves.

For the opposite directions of the system imbalance and the BRP imbalance is the method as follows:

$$IP_j = \frac{\sum_i \sum_n \sum_k ((V_{RE+})_{ij}^{kn} * (P_{RE+})_{ij}^{n} * L_{ij}) + \sum_m ((V_{ORE+})_j^m * (P_{ORE+})_{ij}^n)}{\sum_i \sum_n \sum_k ((V_{RE+})_{ij}^{kn} * L_{ij}) + \sum_m ((V_{ORE+})_j^m * (P_{SOR+})_j)} \tag{27}$$

Where P_{MIP} is the price based on the short-term trades on the energy Exchange („Market Index Price“) and V_{MIV} is the volume based on the short-term trades on the energy Exchange („Market Index Volume“).

5.3.6. Switzerland

Transmission system operator (TSO) in Switzerland is the Swissgrid. PTU in Switzerland is 15 minutes.

The price for the BRP imbalance does not matter on the direction of the system imbalance, but only on the direction of the BRP imbalance. This is therefore dual-pricing imbalance settlement system. The BRP which reach the negative imbalance (shortage) pay the imbalance price and the BRP with the positive imbalance receive the payment.

For the negative BRP imbalance is the pricing method as follows [30]:

$$IP = (MAX[P_{SPOT}; P_{SR+}; P_{TR+}] + P_1) * \alpha_1 \tag{28}$$

Where P_1 is the base for the imbalance price, P_{SPOT} is the spot price, P_{SR+} is the price of the upward regulation energy from the secondary reserve, P_{TR+} is the price of the upward regulation energy from the tertiary reserve and the α_1 is the coefficient. The price for the regulation energy is considered only if this service is activated.

For the positive BRP imbalance is the pricing method as follows [30]:

$$IP = (MIN[P_{SPOT}; P_{SR-}; P_{TR-}] - P_2) * \alpha_2 \tag{29}$$

Where P_2 is the base for the imbalance price, P_{SR-} is the price of the downward regulation energy from the secondary reserve, P_{TR-} is the price of the downward regulation energy from the tertiary reserve and the α_2 is the coefficient. The price for the regulation energy is again considered only if this service is activated.

5.3.7. Belgium

Transmission system operator (TSO) in Belgium is the ELIA, which also make the pricing of the system imbalance. Energy market regulator is the CREG and local market regulators are VREG, CWaPE and BRUGEL. PTU in Belgium is 15 minutes.

The BRP imbalance price depends on the value of the system imbalance. When the system imbalance reach or exceed the threshold of the 140 MWh, to the BRP imbalance price are added or deducted (depends on the direction of the BRP imbalance) coefficients α and β. See Table 2.

Table 2 System Imbalance pricing in Belgium

	Positive system imbalance	Negative system imbalance
Positive BRP imbalance	$MP_{RE-} - \alpha_3$	$MP_{RE+} - \beta_1$
Negative BRP imbalance	$MP_{RE-} + \beta_2$	$MP_{RE+} + \alpha_4$

Where MP_{RE-} is the lowest price of the activated downward regulation energy and MP_{RE+} is the highest price of the activated upward regulation energy. β_1 and β_2 are zero. When system imbalance is less or equal then 140 MWh, α_3 and α_4 are zero. For system imbalance higher or equal then 140 MWh, α_3 and α_4 are dependent on the value of the system imbalance in the last 7 PTU.

$$\alpha_3 = \frac{\hat{y}(SI^{PTU-7}, \dots, SI^{PTU})}{15000} \tag{30}$$

Where $\hat{y}$ is the average of the last 7 PTU and SI^{PTU-7} is the system imbalance lagged by 7 PTU.

$$\alpha_3 = \alpha_4 \tag{31}$$

For the case of usage of the strategic reserve, the BRP imbalance is priced by the set prices.

5.4. System imbalance pricing in the Czech Republic

The price settlement of the system imbalances is set to motivate the BRP to balance their position to zero. The goal of the TSO is to achieve the minimum extreme situation with very high absolute system imbalance, which is needed to balance. The total amount of the balancing (regulation) reserve is limited and in the case of the very high absolute system imbalances is the risk of lack of these reserve and the need of use extraordinary services (as the help of surrounding TSO) for balancing the supply and demand. This goal is fulfilled by the using of the minimum price for the imbalance, which has the dependence between imbalance price and the value of the system imbalance. With the increasing system imbalance, the price for the imbalance increase as well.

Next is a need to ensure appropriate relation between average imbalance price and the price of the electricity power traded in the energy exchange to avoid creation of the intentional imbalances (in the same direction to the system imbalance) in order to gain profit.

As stated in the previous chapter, the Czech Republic's system imbalance is priced in four basic cases:

1) BRP positive imbalance (surplus) with positive system imbalance (surplus);
2) BRP negative imbalance (shortage) with negative system imbalance (shortage);
3) BRP positive imbalance (surplus) with negative system imbalance (shortage);
4) BRP negative imbalance (shortage) with positive system imbalance (surplus).

Each of these cases is priced according to a different methodology. The total payment is calculated by multiplying the system imbalance price and the system imbalance volume. In the rest of the chapter, I use positive payment prices for payment paid to BRPs and negative payment prices for payment paid from BRPs to the TSO. For example, if the BRP has a negative imbalance and the imbalance price is positive, the total payment has the negative sign and the BRP pays to the TSO. For the negative imbalance price the TSO pays to the BRP [13, 25].

1) In the first case, the imbalance price is the minimum from the marginal downward regulation energy price and the threshold price set by the Energy Regulatory Office in

[25]. This imbalance price is most often negative and is paid by the BRP to the TSO (system imbalance volume is negative).

$$IP = min\left[IP_{min}; \min(RP_{REG-}^{sch})\right]\textit{[CZK]} \tag{32}$$

$$IP_{min} = -1 - 3.5 * SI\textit{[CZK]} \tag{33}$$

2) This second case is similar to the first one: the imbalance price is the maximum from the upward marginal regulation energy price and the threshold price set by [25]. This price is most often positive and is paid by the BRP to the TSO (system volume is positive).

$$IP = max\left[IP_{max}; \max(RP_{REG+}^{sch})\right]\textit{[CZK]} \tag{34}$$

$$IP_{max} = 2350 + 5.5 * SI\textit{[CZK]} \tag{35}$$

3) The third case sets the price as the weighted average of the downward regulation price. This price is paid by the TSO to the BRP.

$$IP = \frac{\sum_{\forall BRP} E_{RE-}^{sch} * RP_{RE-}^{sch}}{\sum_{\forall BRP} E_{RE-}^{sch}}\textit{[CZK]} \tag{36}$$

4) The fourth case is set out in the same methodology as the third one. The price is set as the weighted average of the upward regulation price. This price is paid by the TSO to the BRP.

$$IP = \frac{\sum_{\forall BRP} E_{RE+}^{sch} * RP_{RE+}^{sch}}{\sum_{\forall BRP} E_{RE+}^{sch}}\textit{[CZK]} \tag{37}$$

Where:

IP is the imbalance price;

IP_{min} is the minimum price threshold;

IP_{max} is the maximum price threshold;

RP_{REG-}^{sch} is the downward regulation price;

RP_{REG+}^{sch} is the upward regulation price;

E_{RE-}^{sch} is the amount of the downward regulation energy; and

E_{RE+}^{sch} is the amount of the upward regulation energy.

The most frequent regulation energy comes from secondary regulation services. Prices for regulation power are set by the ERU and are 2350 CZK/MWh for upward regulation and -1 CZK/MWh for downward regulation. Thus, in these hours the price for the cases are as follows:

1) $IP = -1 - 3.5 * SI$[CZK/MWh]
2) $IP = 2350 + 5.5 * SI$[CZK/MWh]
3) $IP = -1$[CZK/MWh]
4) $IP = 2350$[CZK/MWh]

The tertiary regulation service changes the price, if it is activated.

The prices for BRP imbalances are shown on the Figure 2, where BRP imbalance is in the same direction as the system imbalance (1. and 2. cases) and on the Figure 3, where BRP imbalance is in the opposite direction as the system imbalance (3. and 4. cases).

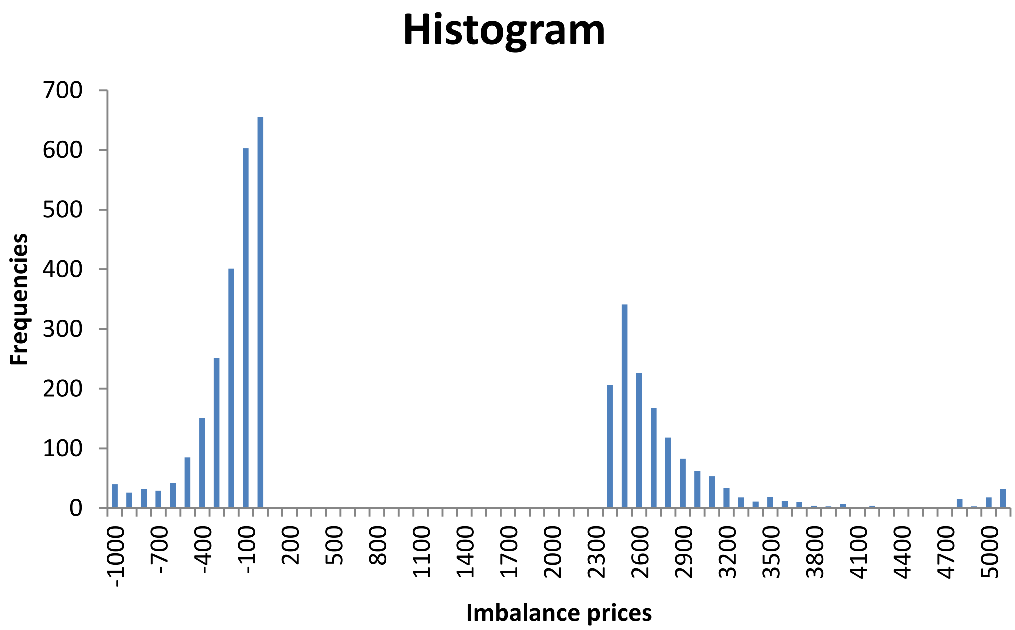

Figure 2 BRP imbalances prices histogram from 24.1. till 29.6.2014. For the BRP imbalances in the same direction as system imbalance. Source: own calculation.

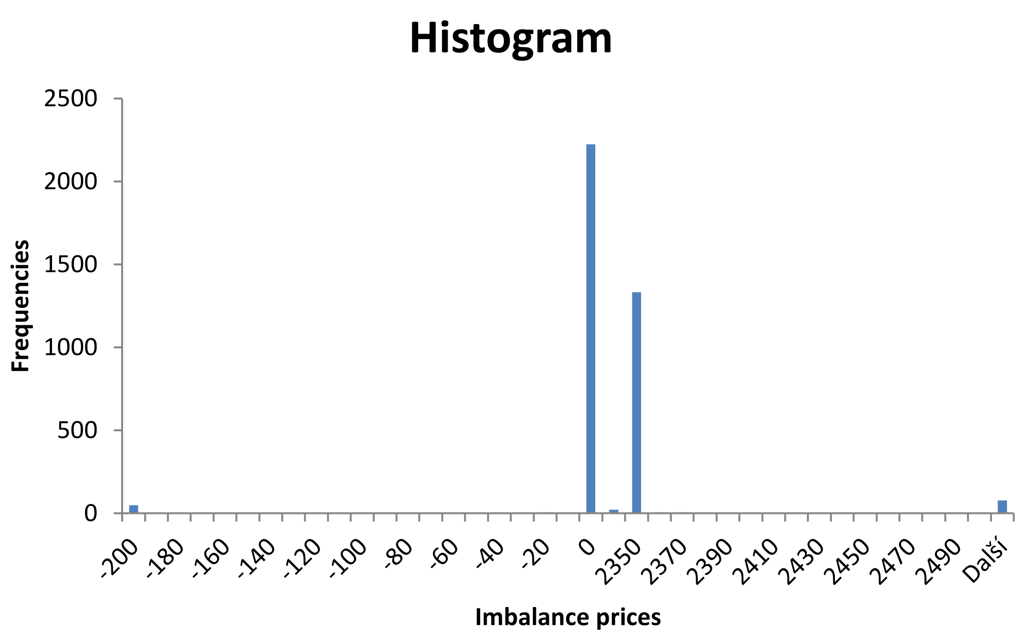

Figure 3 BRP imbalances prices histogram from 24.1. till 29.6.2014. For the BRP imbalances in the opposite direction to the system imbalance. Source: own calculation.

5.4.1. OTE

Pricing of the imbalances is made by the OTE, a.s., who is the market operator under the license no. 150504700, issued by the Energy Regulatory Office pursuant to § 4, point. 3 c) of the Energy Act and the management of a publicly accessible register of trading in emission allowances for greenhouse gases under the Act no. 695/2004 Coll. on conditions for trading in greenhouse gas emissions. Imbalance is evaluated for each PTU, which is one hour for Czech Republic, in MWh with the precision on the one decimal up to 14:00 of the D+1 (following day to the evaluated day).

Each subject trading on the energy market has to be registered at the OTE. Responsibility for the imbalance (BRP = balance responsible party) has only a few members, who is called BRP (balance responsible party), because of the huge amount of energy market participants. BRP's have the contract enclosed with OTE concerning the pricing of the BRP imbalances. BRP have to dispose sufficient financial clearing to be able to cover all trade activities and the imbalances arising from them. They also have to provide real data about supply and consumption needed for settlement of the imbalance. Next market participants enclose the contracts with BRP concerning the delegation of the responsibility for their imbalance. This process leads to creation of the balancing groups, for which is the imbalance priced.

The position of the balancing group is done by the sum of the supply, consumption and cross-border trades across the group in MWh. The trades consist of the trades organized by OTE (day-ahead, intraday and balancing market), trades organized by PXE (month and year future contracts) registered at OTE and bilateral agreements, registered at OTE in the form of the realization diagrams. Next trades are cross border trades in the form of international nominations and trades with regulation energy. All the realization diagrams and cross border nominations have to be confirmed at both counterparties.

6. Analysis of the system imbalance in the Czech Republic

In this chapter, I analyse the time series of the system imbalance in the period from 29 January 2014 to 30 June 2015. The time series can be seen in Figure 4 and its descriptive statistics are presented in Table 3. It is shown that the data are very volatile, with a lot of extreme jumps.

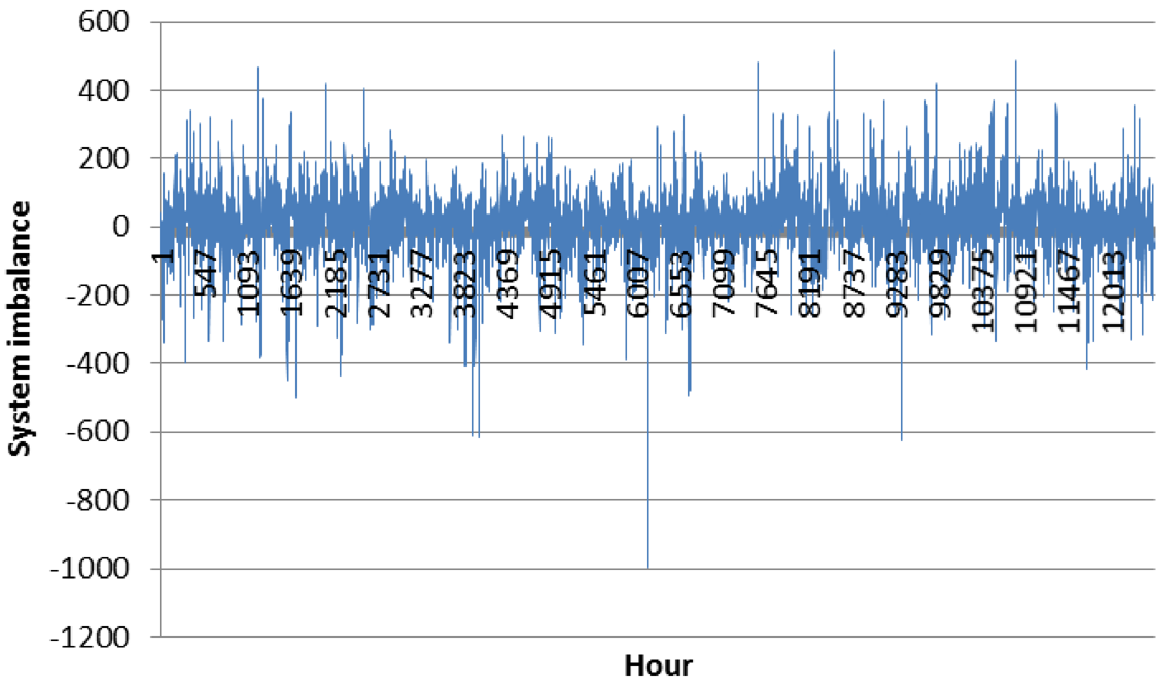

Figure 4 System imbalances from 24 January to 30 June 2015. Source: own calculation.

Table 3 Descriptive statistics of the system imbalances from 24 January 2014 to 30 June 2015. Source: own calculation.

Mean	Median	Std dev	Skewness	Kurtosis	Min	Max	25% qtl	75% qtl
15.96	16.90	89.40	-0.64	7.45	-995.19	515.02	-24.09	59.00

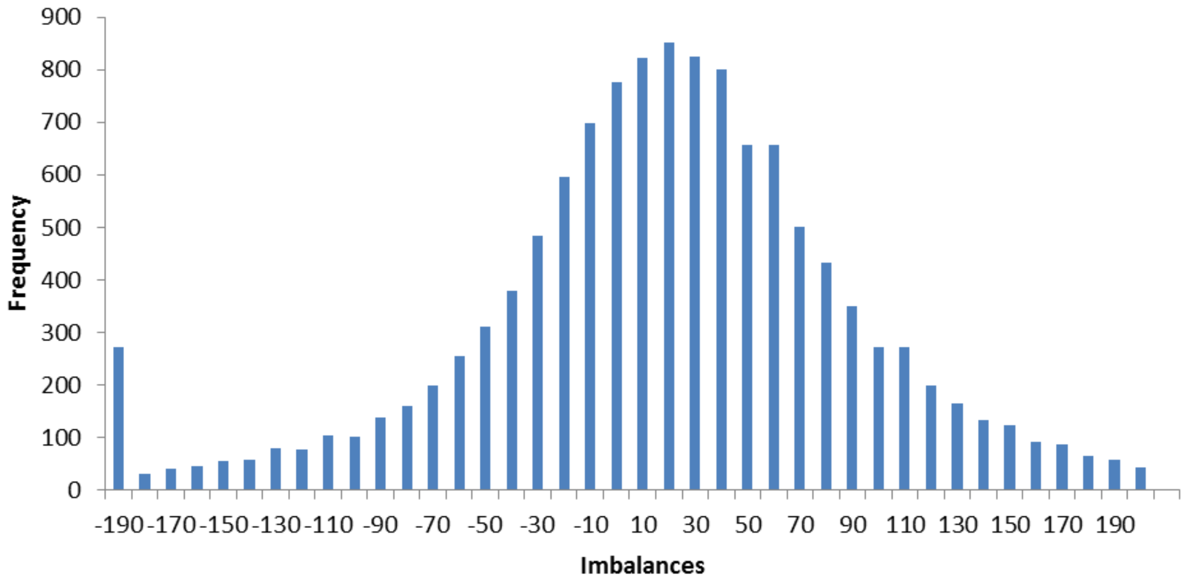

Figure 5 System imbalance volume histogram from 24 January 2014 to 30 June 2015. Source: own calculation.

From the histogram presented in Figure 5 and negative value of skewness, it can be seen that the positive system imbalance (system is in the surplus) is more frequent than the negative system imbalances. The reason is that the price of positive BRP imbalance and positive system imbalance is lower than that of negative BRP imbalance and negative system imbalance.

6.1. Analyses of the development of the BRP imbalances in the same and opposite direction to the system imbalance

To prove the importance of the BRP imbalances in the opposite direction to the system imbalance, I analyse these values in the last years. We can see, on the Figure 6 that in the last 9 years, the total sum of the BRP imbalances in the opposite direction to the system imbalance increased even the BRP imbalance in the same direction to the system imbalance decreased. This influence is also presented on the Figure 7, where the ration between these two values is shown in the graphical way, with strong rising trend of the ratio.

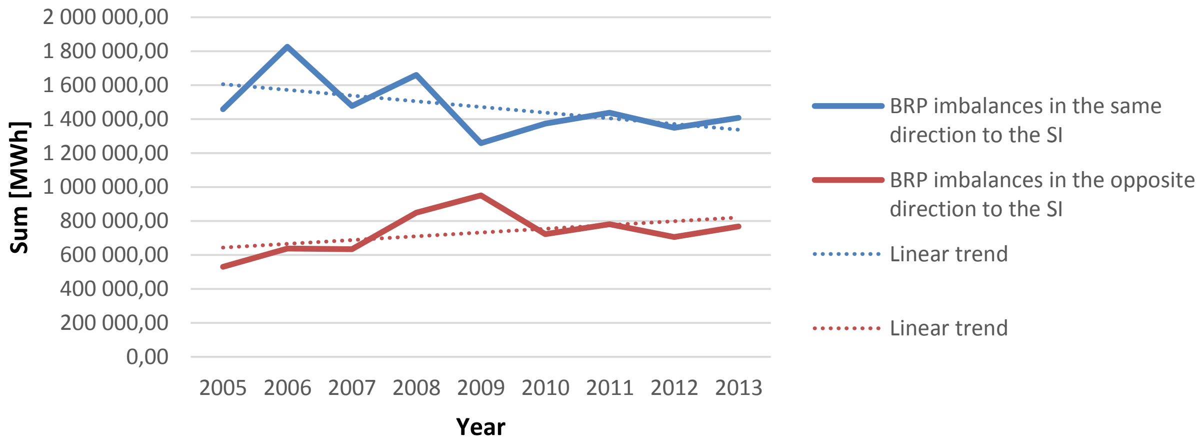

Figure 6 Yearly summed BRP imbalances in the same and opposite direction to the SI. Dotted line presents the linear trends. Source: own calculation.

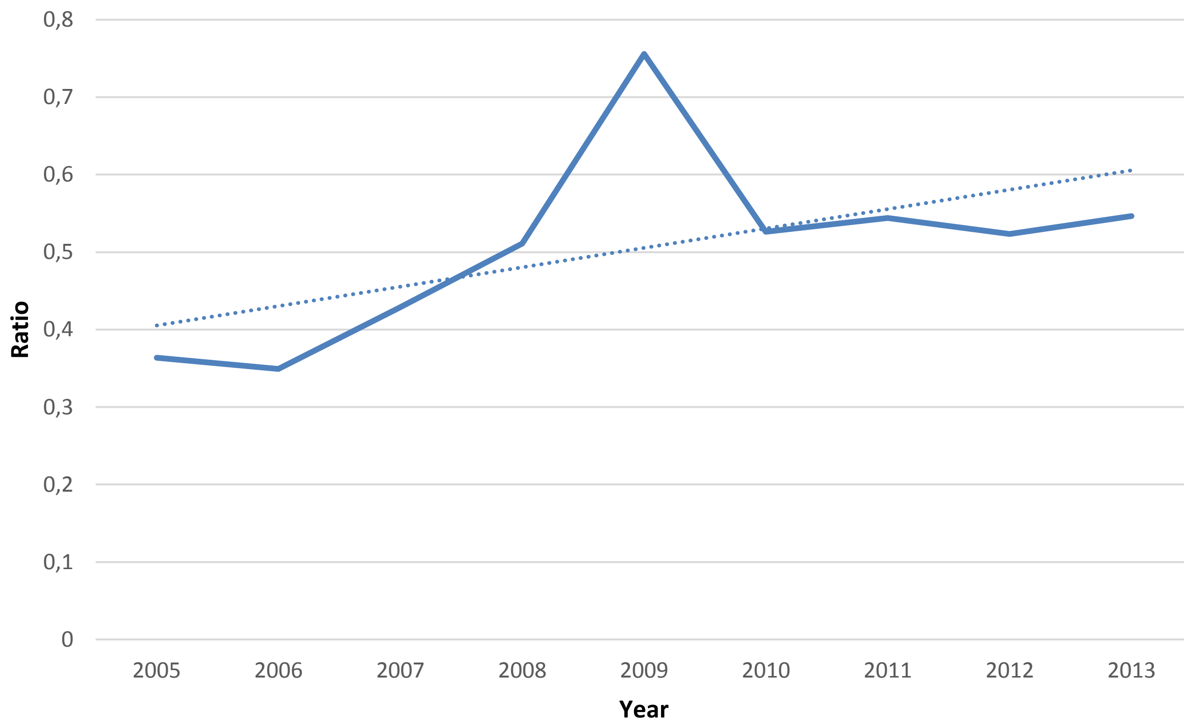

Figure 7 Ratio between BRP imbalances in the same and opposite direction to the system imbalance. Dotted line presents the linear trend. Source: own calculation.

6.2. Seasonality of the system imbalance

The seasonality is a special feature of an electricity and is much stronger at this commodity that at others. As the electricity cannot be stored and has to be balanced in the real time, every change in demand or supply lead to the creation of the system imbalance.

The demand side is the main cause of the creation of the system imbalance seasonal pattern (see Table 4). There are times of a day, when the demand is very low (typical hours from 23:00 till 05:00). In these hours, the supply prevails demand and the system imbalance is typically positive. On the other side, the hours in the peak time (from 08:00 till 20:00) – mainly at the edges of the interval are very often connected with negative system imbalance. This is caused by starting and shutting down the factories, which is connected with increased electricity consumption.

Table 4 Average positive system imbalance occurrence probabilities. Source: own calculation.

OH	1	2	3	4	5	6	7	8	9	10	11	12
SI+ [%]	56.9	59.1	62.9	66.8	66.3	65.7	49.7	45.8	48.6	46.4	50.8	49.1
OH	13	14	15	16	17	18	19	20	21	22	23	24
SI+ [%]	51.3	58.0	57.4	50.2	52.4	58.5	52.4	45.8	49.1	58.0	61.8	64.4

Next seasonal patterns can be observed during different days in the week (mainly differences between weak days and the weekend). At the weekend days cannot be observed effect of the negative system imbalance during peak hours as most of the industry is not operational. All these patterns are displayed in the Table 5 by the percentage probability that the specific hour in the specific day results into the positive system imbalance (the percentage of the probability of the occurrence negative system imbalance can be achieved by subtracting this value from 100%).

Table 5 Average positive system imbalance occurrence probabilities in days of the week. Source: own calculation.

Hour	Monday 1	Tuesday 2	Wednesday 3	Thursday 4	Friday 5	Saturday 6	Sunday 7
1	56.00%	61.54%	34.62%	61.54%	53.85%	61.54%	69.23%
2	64.00%	50.00%	38.46%	61.54%	65.38%	61.54%	73.08%
3	48.00%	65.38%	46.15%	73.08%	73.08%	53.85%	80.77%
4	68.00%	61.54%	42.31%	69.23%	80.77%	69.23%	76.92%
5	72.00%	61.54%	61.54%	53.85%	61.54%	69.23%	84.62%
6	56.00%	53.85%	38.46%	76.92%	61.54%	84.62%	88.46%
7	24.00%	34.62%	30.77%	50.00%	57.69%	65.38%	84.62%
8	36.00%	30.77%	38.46%	50.00%	46.15%	46.15%	73.08%
9	40.00%	30.77%	46.15%	53.85%	46.15%	57.69%	65.38%
10	28.00%	34.62%	46.15%	50.00%	38.46%	65.38%	61.54%
11	32.00%	42.31%	61.54%	46.15%	53.85%	65.38%	53.85%
12	40.00%	46.15%	61.54%	38.46%	42.31%	57.69%	57.69%
13	36.00%	57.69%	57.69%	50.00%	38.46%	57.69%	61.54%
14	44.00%	65.38%	69.23%	46.15%	53.85%	65.38%	61.54%
15	44.00%	57.69%	76.92%	38.46%	53.85%	65.38%	65.38%
16	40.00%	38.46%	69.23%	42.31%	42.31%	65.38%	53.85%
17	36.00%	53.85%	61.54%	38.46%	50.00%	65.38%	61.54%
18	40.00%	42.31%	61.54%	57.69%	50.00%	76.92%	80.77%
19	36.00%	50.00%	42.31%	61.54%	69.23%	53.85%	53.85%
20	40.00%	38.46%	30.77%	50.00%	65.38%	50.00%	46.15%
21	48.00%	50.00%	30.77%	61.54%	57.69%	53.85%	42.31%
22	56.00%	53.85%	46.15%	57.69%	61.54%	76.92%	53.85%

23	56.00%	50.00%	53.85%	73.08%	65.38%	80.77%	53.85%
24	60.00%	65.38%	69.23%	65.38%	57.69%	73.08%	57.69%
25	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

6.3. Balancing system imbalance

The basic definition of the system imbalance is that it is a difference between total supply and total demand. This definition implies that behaviour of the system imbalance is influenced by the behaviour of these two inputs.

One of the key features of the electricity is its non-storability. Electricity cannot be stored in some sufficient amount, so that the demand and supply has to be balanced in the real time. As it is pretty hard to influence the amount of demand (in a short time), the balance is more on the side of supply. Energy sources, which can change their generation level quickly, are used to balance the amount of the energy in the grid. For these purposes, these sources provide services to the TSO, which are connected with providing regulation energy. These services has to have the capacity for covering the biggest generation source in the grid (for Czech Republic one block of the nuclear power plant Temelin, which is 1020 MW). Basic three services for balancing the power grid are defined in this chapter. These are follows:

1. Primary regulation: This service is used for balancing current frequency. Lower supply leads to decrease of the frequency and providers of the primary regulation has to increase their generation and opposite. This service is common for the whole European power grid and is activated automatically by the TSO.
2. Secondary regulation: This service balances the surplus or shortage in the power grid (in the sense of amount of the energy). Most of the time, the power grid is balanced only by this service, which is activated automatically by the TSO.
3. Tertiary regulation: This service is used, when the secondary regulation is not capable to cover all the surplus or shortage of the power grid. It is not used too often as it is more expensive for the TSO to active this service (ask for delivery of the regulation energy). Tertiary regulation is not activated automatically by the TSO, but every provider has to do it manually after direction from the TSO.

Contracts for these services are traded in year auction (which prevail) and day-ahead auction. Generators, which want to provide these services, have to be certified for that[7].

Similar type of balancing of the system imbalance is also used by European states [24].

6.3.1. CEPS

CEPS a.s., which is an abbreviation of the Czech electricity transmission system, is the company operating electricity transmission networks (electric lines and equipment 400 kV and 220 kV) in the Czech Republic on the basis of a license according the Energy law No. 458/2000 Coll. Maintains, restores and develops 41 substations with 71 transformers transferring electricity from the transmission to the grid, routes and lines with voltage level of 400 kV with a length of 3508 km of 220 kV with a length of 1910 km.

CEPS provides transmission services in the Czech Republic and dispatching ensures a balance between production and consumption of electrical energy at any given moment. CEPS is specifically responsible for the stability of the power and frequency, voltage regulation and reactive power. For ensuring the stability of the parameters listed CEPS market purchases necessary power reserves in the form of primary, secondary and tertiary reserve (more in Chapter XY.)

Simultaneously, the company is integrated into European structures. CEPS cooperates with neighboring TSOs in Germany, Poland, Austria and the Slovak Republic, as well as with partners in Central and Eastern Europe (CEE - Czech Republic, Slovakia, Germany, Austria, Poland, Hungary and Slovenia) and it is a member of ENTSO-E.

ENTSO-E (the European Network of Transmission System Operators) is an association of 41 European TSOs from a total of 34 European countries - EU and non-EU countries. ENTSO-E, its content and links to other Community bodies are derived from European energy legislation - the so-called Energy third liberalization package. The main objectives of the association ENTSO-E strategy include completing the internal market and cross-border trade with electricity, ensuring optimal management and development of the European electricity transmission network as part of their coordinated cooperation. One of the most important activities of ENTSO-E is the creation of the network codes, which are as binding documents become part of the secondary EU legislation.

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[7] http://www.ceps.cz/CZE/Data/Legislativa/Kodex/Documents/%C4%8C%C3%A1stII_14_fin.pdf

From the point of view of the system imbalances, CEPS participates in Grid Control Cooperation - GCC and e-GCC. This international project extends the possibility of cross-border exchange of balancing energy (i.e. the energy needed to compensate for the deviation between the current generation and consumption of electricity) with European transmission system operators. This project can reduce the cost of regulation energy while maintaining the proven structure of the regulatory regions in terms of safe and continuous transmission. CEPS is currently involved in two international projects:

- e-GCC - along with transmission system operators from Slovakia and Hungary.

- IGCC (International Grid Control Cooperation) - together with the TSOs from Germany, Denmark, the Netherlands, Switzerland and Belgium.

CEPS allocates by auctioning transmission capacity for export, import and transit of electricity. The company is also involved in the formation of the electricity market in Europe.

7. System imbalance intra-hour trend

Maintaining the system imbalance in the desired range is essential for the stability of the transmission network. Increasing production of intermittent sources, the technical condition of classic production capacity and interconnected European market cause complications during the operation of the power system, the system deviation is basically the most important parameter in monitoring the overall stability.

For the great majority of participants in the electricity market is ultimately important especially average hourly system imbalance, since their imbalances are evaluated according this value. However, monitor and forecast the system imbalance intra-hour development is very important not only for producers of electricity (the ability to adjust their position within the current hour), but especially for the transmission system operator (CEPS a.s.), who is responsible for balancing the system deviations in real time. This balancing of production and consumption with regard to cross-border flows and losses in networks is done with support services (PR, SR, MZ, SV, re-dispatch etc.). CEPS are obliged to buy these services by law from providers of support services up to the largest block in the network (block Temelin nuclear power plant with an output of 1020 MW). This regulation reserve, however, is no longer sufficient keeping in mind the increasing installed capacity of intermittent renewable energy sources. In combination with outages of classic sources of electricity, the exhaustion of reserves to balance the transmission system can lead to crisis scenarios buying regulating power abroad, reducing consumption, and in the worst case, to decrease the frequency that causes the disintegration of the system and the formation of partial market grids and the places without electricity.

By the analysis of the critical situation in 10. and 11. 9. 2015 of the unscheduled outage of the Chvaletice Power Plant, and Temelin was found that given 1020 MW reserve was nearly exhausted, when the system imbalance exceeds the value of -800 MW [26]. For these times it is necessary to accurately forecast the intra-hour development of the system imbalances, because even if average hourly value of the system imbalance is less than the limit of 1 020 MW, exceeding the limit in just a few minutes can lead to critical consequences mentioned above.

This situation leads to the question how to forecast intra-hour development of the system imbalances. It was found that there was no public discussion of the methodology, which could be successfully applied in solving this issue.

7.1. Intra-hour trend forecast methodology

The key idea of the proposed approach is to use all known fundamentals involved in the formation of the system imbalance for the prediction of it. For intra-hour prediction it is necessary to use the conflict between the hourly evaluated period of the electricity market (electricity trading, settlement of deviations, the calculation of regulatory power) and balancing production and consumption in real time (or in one-minute data - shorter and more detailed data are not available). Consumption is therefore with an increase growing throughout hours, but the production of electricity is in a given hour constant. Here is meant mainly the production in conventional types of power plants (for the Czech Republic it is nuclear and coal power plants). Production imbalance is visible only at the end of hours, when it is necessary to change the power level to set the power level corresponding to the average consumption for the current hour - but this change takes a few minutes and the rest of the hour is almost constant. Increasing intra-hour trend in consumption (typically hours in the morning) causes a surplus situation at the beginning of the hour, which changes in to a shortage in the half of an hour. The opposite situation can be observed in declining intra-hour trend in consumption.

Another intra-hour way of formation may be caused by variable intermittent production of renewable sources of electricity. These sources are for Czech Republic mainly photovoltaic power plants, which change in the morning its output from zero to full production within a few hours. This development is again a negative impact on the destabilization of the system imbalance by increasing the minimum and maximum values of the intra-hour system imbalances. The opposite situation can be observed again in the evening, when there is a decrease in electricity production from this source type with decreasing intensity of sunlight.

Another factor influencing the development of the intra-hour system imbalances are speculations on achieving the opposite direction of the balance responsible party imbalance to the direction of the system imbalance. There is a need to analyse progress and to detect the moment, when the estimation of the intra-hour imbalance is stable enough for the prediction of the average total system imbalance for the hour. For the rest of an hour, there is a need to count with the trend of electricity producers regulating their position in order to achieve the opposite direction of the balance responsible party imbalance to the direction of the system imbalance. This trend is the maximum technical limit of changing the production of considered plants.

All these aspects must be included in the model of the forecasting the intra-hour development of the system imbalance and correct setting weighting of the inputs to achieve the greatest possible accuracy of the prediction. [51]

7.2. Minute vs. hour system imbalance

I have made statistically analysis of the intra-hour system imbalance data in the period from January till February 2016. The data set has about 86 400 samples, which is sufficient amount for our research. Data are displayed at the Figure 8. At the Figure 9, there is for comparison data set of average hourly data. In the Table 6 are presented descriptive statistics of the examining data, from which we can see the differences between intra-hour and hour data set. Intra-hour data set are much more volatile than hourly data set of system imbalance. Maximum value by the intra-hours data is more than 70 % higher than by average hour data and minimum value is less than 60 %. Standard deviation is by intra-hour values even more than 60 % higher.

The difference between the data is also caused by the time interval of the data evaluation as the intra-hour data are collected at the real time and hourly data come from the daily evaluation of the imbalances made by OTE at 14:00 the following day. These differences are not so important to data would not be comparable.

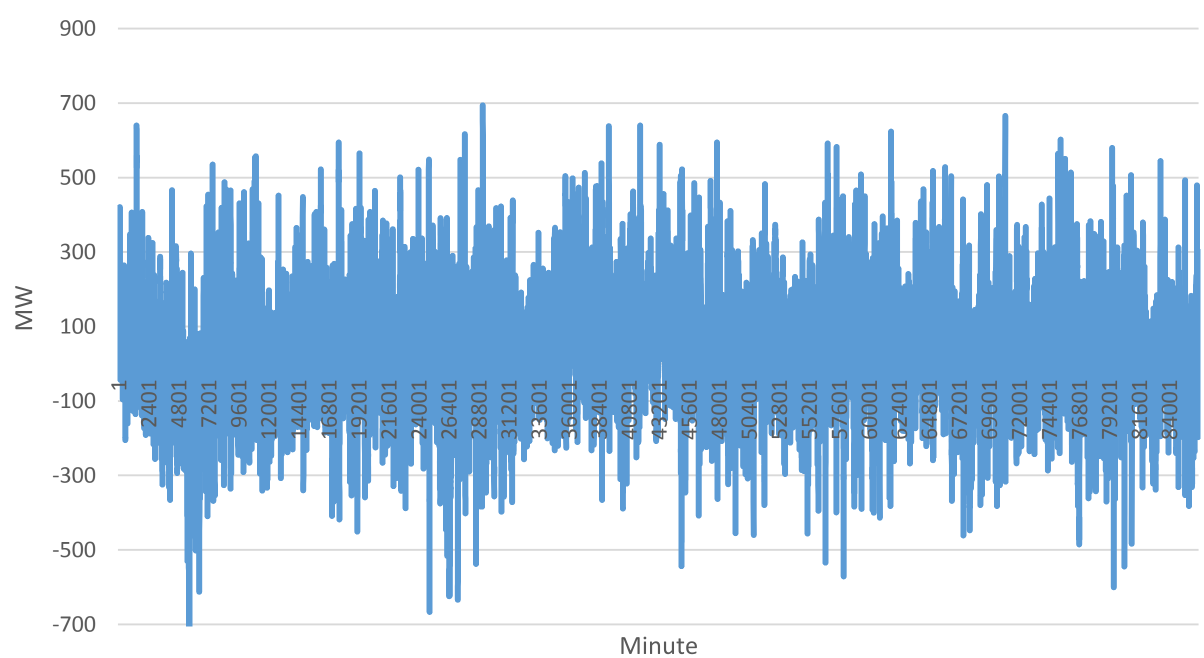

Figure 8 Graphical presentation of the intra-hour system imbalance from 1.1.2016 till 29.2.2016. Source: www.ceps.cz.

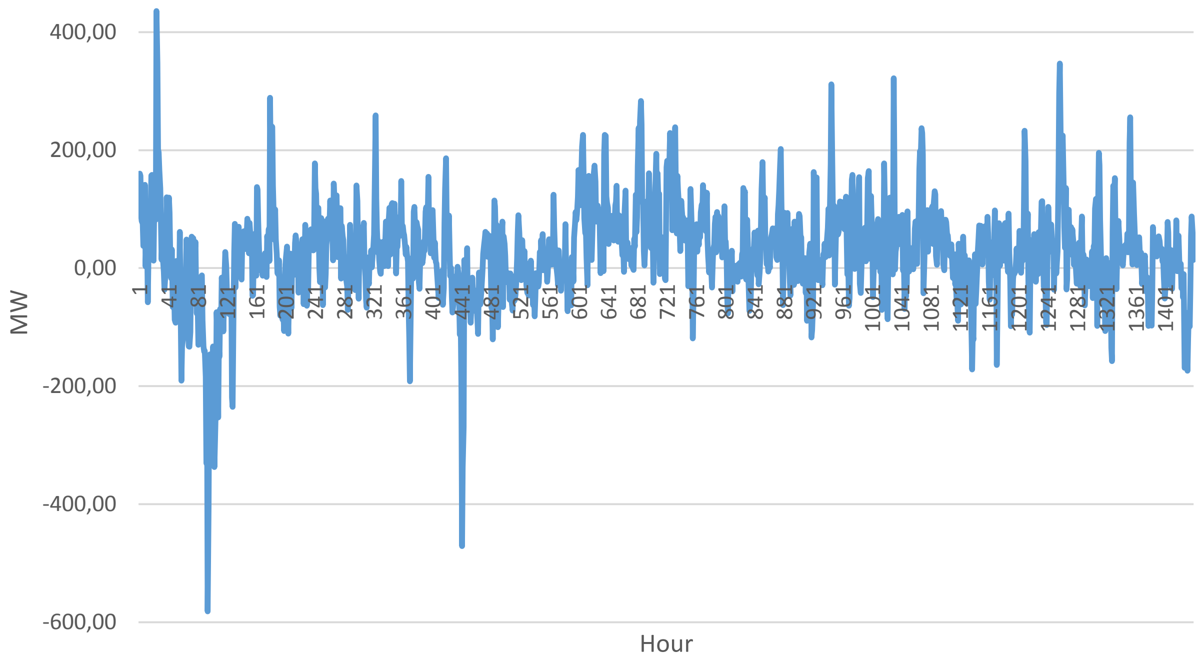

Figure 9 Graphical presentation of the hour system imbalance from 1.1.2016 till 29.2.2016. Source: www.ote-cr.cz.

It is obvious that higher granularity brings more precise view on the data set which is desirable. In average hourly data set can be seen a loss of accuracy – this can be represented by the flatter Figure 9 compared with Figure 8. Higher accuracy can be used to better understanding of the system imbalance and the behaviour of the participants of this market.

There is a difference between mean and median values for intra-hours and average hour data (see Table 6) however from the statistically point of view, there shouldn't be any discrepancy. This is due to source of data. Intra-hour data origins from CEPS, while average hourly data source is OTE. OTE publishes its data delayed reflecting some adjustments in order to be more accurate.

Table 6 Descriptive statistics of the time series of intra-hour and hour system imbalance from 1.1.2016 till 30.6.2016.

Source: own calculations.

	Mean	Median	Std dev	Skewness	Kurtosis	Min	Max	25% qtl	75% qt
intra-hour	26.87	28.5	130.6	-0.19	2.14	-990	694	-48.275	102.00
hour	27.53	27.70	80.9	-0.55	5.77	-581.88	435.82	-12.16	69.67

Higher granularity also showed that some extreme values of the 60 minutes data set of each hour (especially the outer ones) are not corresponding to the inner ones. Respecting this fact could be following research done more precise by cutting of the outer values. The appropriate quintile could then represent each hour.

7.3. Seasonal pattern

We have searched for seasonal patterns in intra-hour data set of January and February (especially hours, days, days in weak and weeks). The most important seasonal pattern is seen by hour analyses. However the direction of the system imbalance was in every hour the same - which is seen in the Figure 10, the directive of the system imbalance was fluctuating during the day (even if there was an increase in average hourly data the average directive was positive and vice versa) – see Figure 11. This shows the added value of higher granularity given by the intra-hours data.

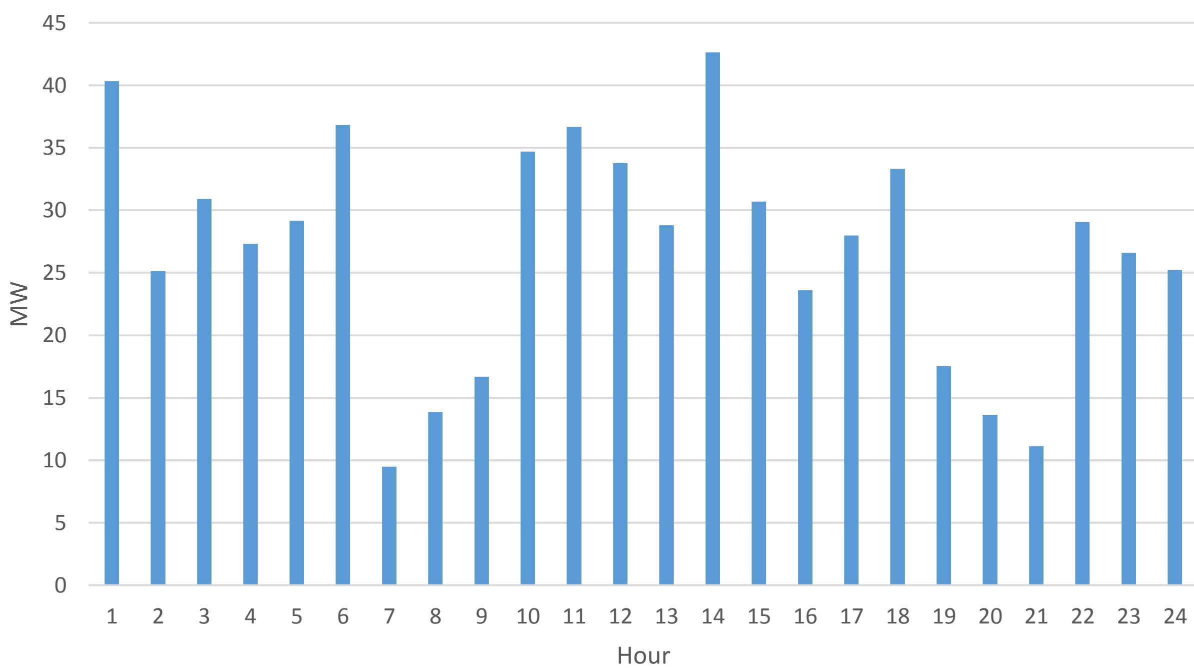

Figure 10 Graphical presentation of the average intra-hour system imbalance from 1.1.2016 till 29.2.2016 in specific hours per day. Source: www.ceps.cz.

In contrast with the average hourly data, the intra-hours data for individual months are very similar to Figure 11 which shows the suitability of using the directives for system imbalance prediction.

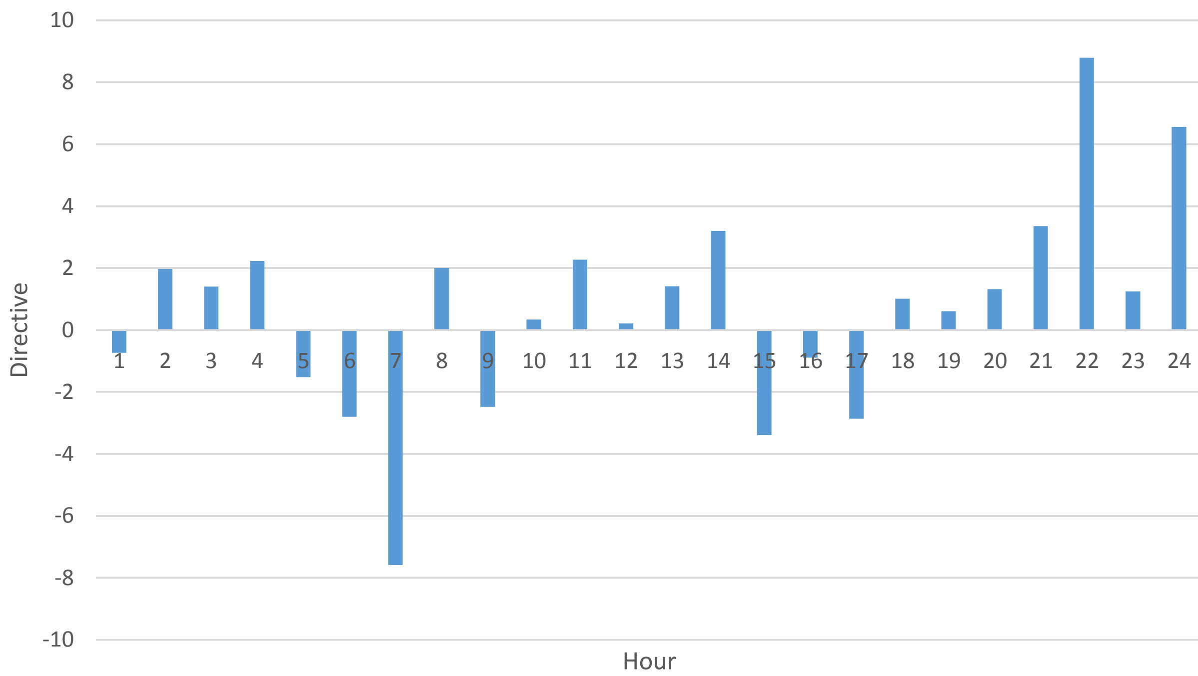

Figure 11 Graphical presentation of the average intra-hour directive of the system imbalance from 1.1.2016 till 29.2.2016 in specific hours per day. Source: own calculation.

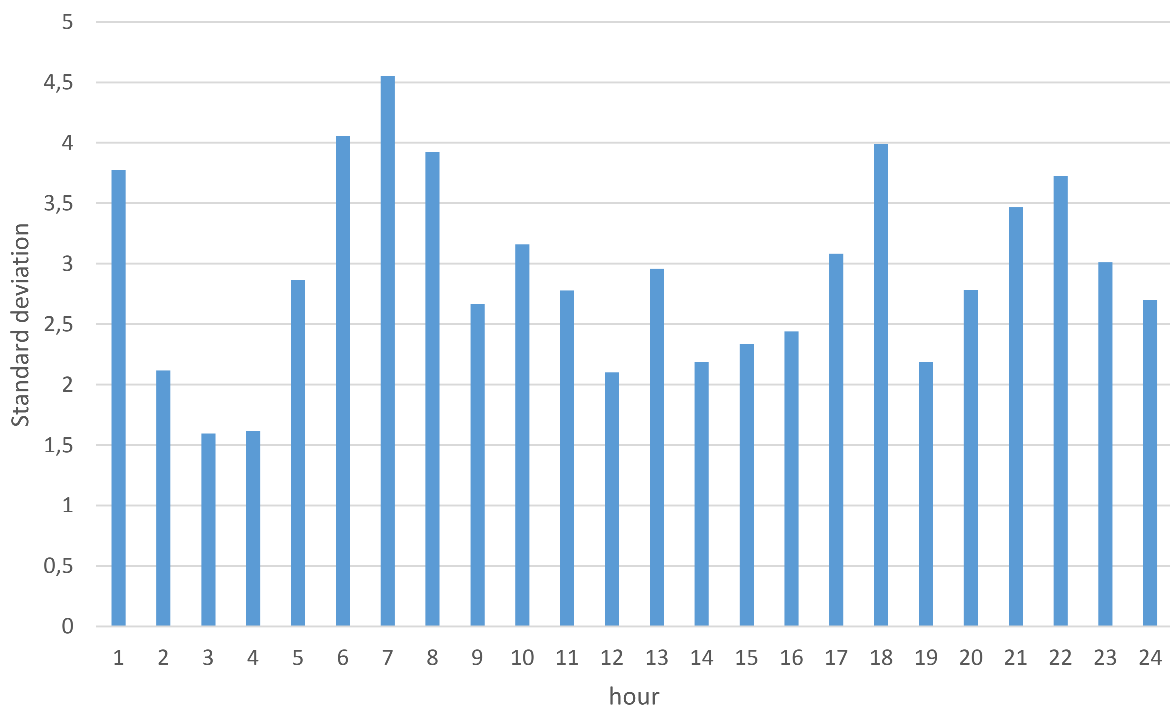

Figure 12 Graphical presentation standard deviation of the intra-hour directive of the system imbalance from 1.1.2016 till 20.2.2016 in specific hours per day. Source: own calculation.

From the Figure 12 it is obvious that in several hours is much higher volatility than in the other ones. This is helpful in case of speculating on the opposite direction of the system imbalance. Similar to the Figure 10 and Figure 11 is here the added value of the higher granularity. In case of evaluating only average hourly data, the standard deviation is almost the same of every hour except hours 7 and 22.

Output from the statistically analysis is also the fact, that the highest value of system imbalance was on Saturday while the lowest was on Tuesday, Wednesday and Thursday. The standard deviation doesn't depend on the day of the weak. The lowest average directive was on Saturday.

7.4. Impact of speculation on the system imbalance

I made a hypothesis that market participants influence the system imbalance by speculation on the opposite direction of their imbalance to the system imbalance. This would mean that at some point the system imbalance would change its trend by speculating market participants, who would be sure that their speculation does not change the direction of the system imbalance. To verify the influence of the behaviour of the market participants on the system imbalance we made the analyses of the intra-hour change of trend of the system imbalance.

The analyse is based on the filtered data, so there remained 40 minutes data except 10 minutes quartiles on each side. We defined three intervals – 20, 30 and 35 minutes after which should change the slope of the system imbalance of the remaining minutes data set. Each trend of the system imbalance was taken only if the system imbalance (from the first minute to the end of the interval) was greater than appropriate pre-defined value of the system imbalance.

Table 7 Analyses of the speculative behaviour of the market participants. Based on the data from time series from 1.1.2016 till 30.6.2016. Source: own calculations.

	Trend 20/20		**Trend 30/10**		**Trend 35/5**	
System Imbalance	**Count of changes**	**Share of changes**	**Count of changes**	**Share of changes**	**Count of changes**	**Share of changes**
0	1 760	25.2%	1 728	24.7%	1 962	29.0%
50	1 386	25.5%	1 094	24.5%	1 098	29.9%
100	848	25.3%	521	23.8%	349	29.1%
150	398	23.8%	126	24.3%	137	28.0%
200	103	21.7%	114	26.8%	66	29.2%

The system imbalance value should help to distinguish the hours, where it is possible to speculate on the opposite direction of BRP imbalance to the system imbalance. If the system imbalance is too small, it is too risky to speculate because of the risk to change the direction of the system imbalance by own speculation. So only the greater values of the system imbalance make sense to speculate. 20/20 means that the change of the trend is considered for the first and second twenty minutes of the data set for each hour. So if (after data filtering) in the first twenty minutes there is a growth rate and in the next twenty minutes the trend becomes decay that is the case of change of the trend (and vice versa for the opposite trend direction).

From the Table 7 it is obvious that the hypothesis of the impact of the market participants was not confirmed. There is no implication that could lead to confirm it. Neither the change of trend nor the change of the value of the system imbalance has significant impact on the share of the changes of the trend. The share of all variants is less than 30 % which is statistically insignificant.

7.5. Intra-hour model description

Hourly trend

Model is based on the methodology described in the 7.1. chapter. As an input variables were used the data of forecasted demand and the supply from PV (forecast made by Thompson Reuters by the EC model [36]) at 12:00 in the previous day to the forecasted day. In each hour was forecasted generation from PV deducted from forecasted demand, which gives us the value of the variable intra-hour system imbalance. Deducting 2 following hours give us the change between neighbouring values. The equation is presented as follows:

$$Var_t = Demand_t - PVsupply_t \tag{38}$$

Where $Var_t$is the variable value of the intra-hour system imbalance, $Demand_t$ is the hourly forecasted value of the total demand and $PVsupply_t$ is the hourly forecast value of the total supply from PV.

The intra-hour system imbalance trend can be obtained by deducting the neighbouring variables values of the intra-hour system imbalance as follows:

$$SItrend_{t,A} = Var_t - Var_{t-1} \tag{39}$$

In this case, we used only previous hour to the forecasted hour for the forecast of the intra-hour system imbalance trend. I use also the next hour as is presented in Equation XY (marked as B):

$$SItrend_{t,B} = Var_{t+1} - Var_t \tag{40}$$

The last forecast is done by using both models and makes a forecast only in cases, where both models forecast the same direction of the trend. This leads to the decreasing of the number of forecasted hours, but increase the accuracy of the successful forecast.

Half-hourly trend

Half-hour trend is based on the hypothesis, that system imbalance intra-hour trend in the first 30 minutes of an hour is influenced only by previous hours and the change between previous and forecasted hour.

7.6. Intra-hour out - of sample forecast

According to the methodology described in chapter 3 was data in the period from 3.1.2016 till 30.6.2016 used for the out-of sample forecast. The results of the forecast can be seen in the Table 8. There can be seen that the forecast based both on previous and following hour with accuracy 79,4 % is much more accurate than the forecasts based just on previous hour (accuracy 67,5%) or following hour (accuracy 67 %). The next result is that forecasting only half of an hour based only on the corresponding hour is not so accurate as forecasting the whole hours. Forecast of the first half of an hour (from 1. till 30. minute) resulted in the accuracy of 57,5 % of successful forecasted trends and the forecast of the second half of an hour (from 31. till 60. minute) resulted in the accuracy of 65,8 % of successful forecasted trends.

Table 8 Forecast of the intra-hour (whole and half of an hour) from 3.1.2016 till 30.6.2016.

Source: own calculations

	Quantity	Successful forecasts	Accuracy
Hourly trend based on t-1	4 319	2 914	67.5%
Hourly trend based on t+1	4 319	2 895	67.0%
Hourly trend based on combination of t-1 and t+1	2 534	2 012	79.4%
Half-hour trend (1. - 30. minute) based on t-1	4 319	2 484	57.5%
Half-hour trend (31. - 60. minute) based on t+1	4 319	2 844	65.8%

Next I try to use filtered data as was presented in the previous chapter. I use the data filtered by 5 minutes, which mean, that first and last 5 minutes of each hour are removed from the original data sample, while computing the intra-hour trend. From the Table 9 we can see that the results are very similar. At some forecasts, the accuracy is higher, at another the accuracy is lower.

The forecast based both on previous and following hour has accuracy 79,5 %, the forecasts based just on previous hour has accuracy 68,6% and or following hour has accuracy 66 %. Forecast of the first half of an hour (from 1. till 30. minute) resulted in the accuracy of 68,9 % of successful forecasted trends and the forecast of the second half of an hour (from 31. till 60. minute) resulted in the accuracy of 64,9 % of successful forecasted trends.

Table 9 Forecast of the intra-hour (whole and half of an hour) from 3.1.2016 till 30.6.2016. 5 minutes filtered data.

Source: own calculations

	Quantity	Sucesfull forecasts	Accuracy
Hourly trend based on t-1	4 319	2 961	68.6%
Hourly trend based on t+1	4 319	2 852	66.0%
Hourly trend based on combination of t-1 and t+1	2 534	2 014	79.5%
Half-hour trend (1. - 30. minute) based on t-1	4 319	2 975	68.9%
Half-hour trend (31. - 60. minute) based on t+1	4 319	2 805	64.9%

Filtering of the data at the beginning and the end of each hour did not lead to the significant improvement in the way of accuracy of the intra-hour system imbalance trend.

7.7. Intra-hour trend and system imbalance value dependence

In this chapter, I analyse, if there is the relation between the trend of the intra-hour system imbalance and the average hour value of the system imbalance (average of the minute’s values). On the Table 10 can be seen, that there is no significant dependence between these two data as the distribution of the probabilities in the table is relatively uniform.

Table 10 Dependence between the trend of the intra-hour system imbalance and the average hour value of the system imbalance (SI). Source: own calculations

SI/trend	< 0	> 0
< 0	941	591
> 0	1 537	1 250

7.8. Intra-hour trend of the system imbalance conclusion

Statistical analysis showed that higher granularity represented by intra-hours values brings more precise view on the data set – see Table 6. There were also identified some seasonal patterns in intra-hour data set. The most important seasonal pattern is seen by hour analyses – see Figure 11 and Figure 12; which gives the added value to new methodology.

Figure 12 also shows that in several hours is much higher volatility than in the other ones. In case of evaluating only average hourly data, the standard deviation is almost the same except hours 7 and 22 and it doesn't depend on the day of the weak. Output from the statistical analysis is also the fact that the highest value of system imbalance was on Saturday while the lowest was on Tuesday, Wednesday and Thursday.

I made a hypothesis that market participants influence the system imbalance by speculation on the opposite direction of their imbalance to the system imbalance – this would lead (at some point) to the change of the system imbalance trend because speculating market participants would be sure that their speculation does not change the direction of the system imbalance. The analyses of the intra-hour change of the trend didn't confirm this hypothesis. The share of changes of the trend at all considered variants was less than 30 % (see Table 7) which is statistically insignificant.

The forecast of the intra-hour trend of the system imbalance showed promising results. The model based on the changes of the demand and the supply of RES power generation (Renewable energy sources) between previous and forecasted hour returned better results than the model based on the changes of the demand and the supply of RES power generation between forecasted and following hour. The best results was achieved by the combination of both of these models and making a forecast only in the hour, where is the partial forecast of both models identical. Forecast is therefore made only in 2534 hours (59 % of the whole data set), but the accuracy arises from 67,5 % (67 %) to 79,4 % of the successfully forecasted intra-hour system imbalances trends. The filtration of the beginning and the last 5 minutes of each hour did not bring the expected improvement and was evaluated as insignificant.

At the end I evaluated the dependence of the system imbalance intra-hour trend and the average hourly system imbalance value. It was proven that there is no significant relationship between these two data so the system imbalance intra-hour trend cannot be used for the forecast of the average system imbalance.

8. New approach to system imbalance forecasting

The exogenous variables that could affect the system imbalance are the basis of the new approach to forecasting system imbalances. After their interval analysis (in combination with system imbalance), I define the most appropriate variables as an input data for the forecast model. The final recommendation for the speculation depends on the opportunity costs on the short-term market.

These variables have to be held properly in the sense of use all the information, which they can offer. Input variables are used both in their numeric values and in the differential values. Differential values can be obtained by deduction of the neighbouring values of the input variable (to get the step change in the data, which could influence the system imbalance value significantly). Differential values can be got as follows:

$$Change_t = IN_t - IN_{t-1} \tag{41}$$

Where $Change_t$ is the differential value of the step change in the time t, IN_t is the input variable in the time t and IN_{t-1} is the input variable in the time t -1.

Another way, how to get the differential value, is by deduction of the concrete input variable and some another input variable (for example planned values and actual measured values to get difference between plan and the reality).

$$Diff_t = Plan_t - Actual_t \tag{42}$$

Where $Diff_t$ is the differential value of the planned and actual measured value of the input variable in the time t, $Plan_t$is the planned input variable in the time t and $Actual_t$ is the actual measured input variable in the time t.

Descriptive statistics of the all inputs can be seen on the Table 35.

8.1. Exogenous variables

As stated above, I differ from previous papers by incorporating multiple exogenous variables in our model. The variables can be divided into three main classes: the demand variable, supply variables and variables incorporating behaviour of other market participants. The following sub-chapters describe the input variables used in the case study. For the application of the methodology on another market, it is necessary to adjust the structure of the input variables according to the local market conditions.

8.1.1. Demand variable

This variable is presented on the web site of the Czech TSO[8]. It is the summation of all demand of all consumers in the Czech Republic's power grid. The data are presented hourly with a one-hour delay. The planned amount of demand is presented in the web system of the TSO[9] the day ahead. By taking the difference between the planned value and the actual demand, I get the demand contribution to the system imbalance creation.

Total really measured consumption is presented on the Figure 13 and its descriptive statistics in the Table 11. These data describe the total consumption of the whole Czech energy grid in the hour average values.

[8] http://www.ceps.cz/CZE/Data/Vsechna-data/Stranky/Zatizeni.aspx

[9] https://dae.ceps.cz/default.aspx

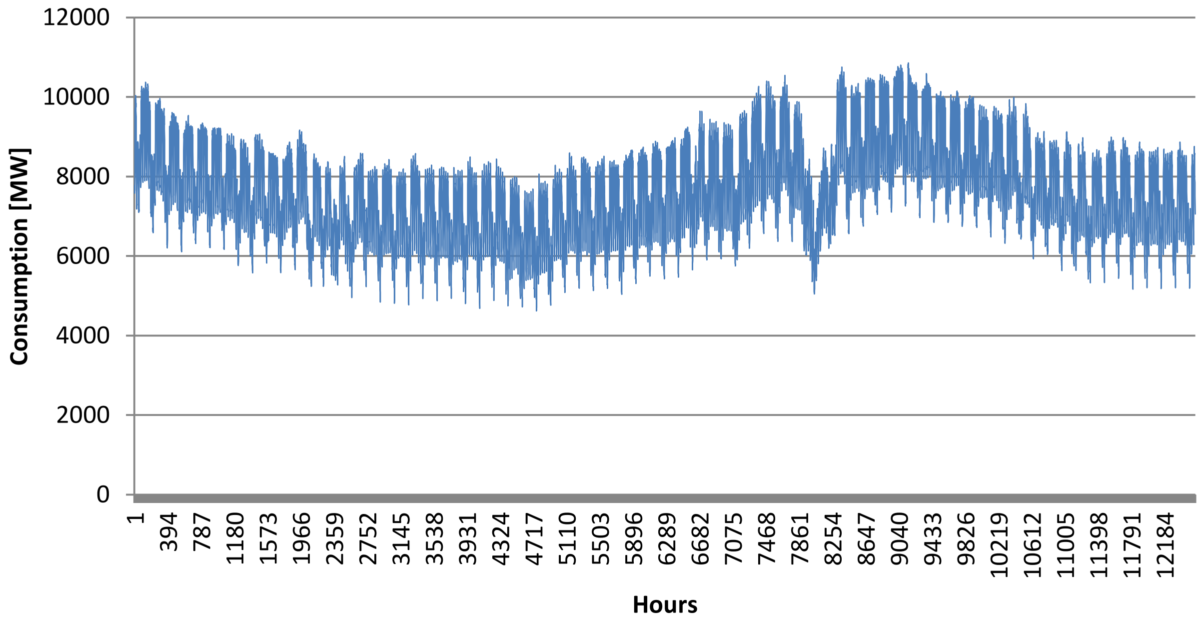

Figure 13 Total measured consumption in the Czech Republic in the date from 29 January 2014 to 30 June 2015.

Source: www.ceps.cz.

Table 11 Descriptive statistics of the total measured consumption in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	7698.03	7708.80	1233.03	0.16	-0.59	-0.60	10855.28	6722.62	8517.10

To express the step change of the consumption in the Czech energy grid, I use the data of the change between neighbouring values (hours) of the total consumption in the Czech grid.

The change between neighbouring values (hours) of the total measure consumption is presented on the Figure 14 and its descriptive statistics in the Table 12.

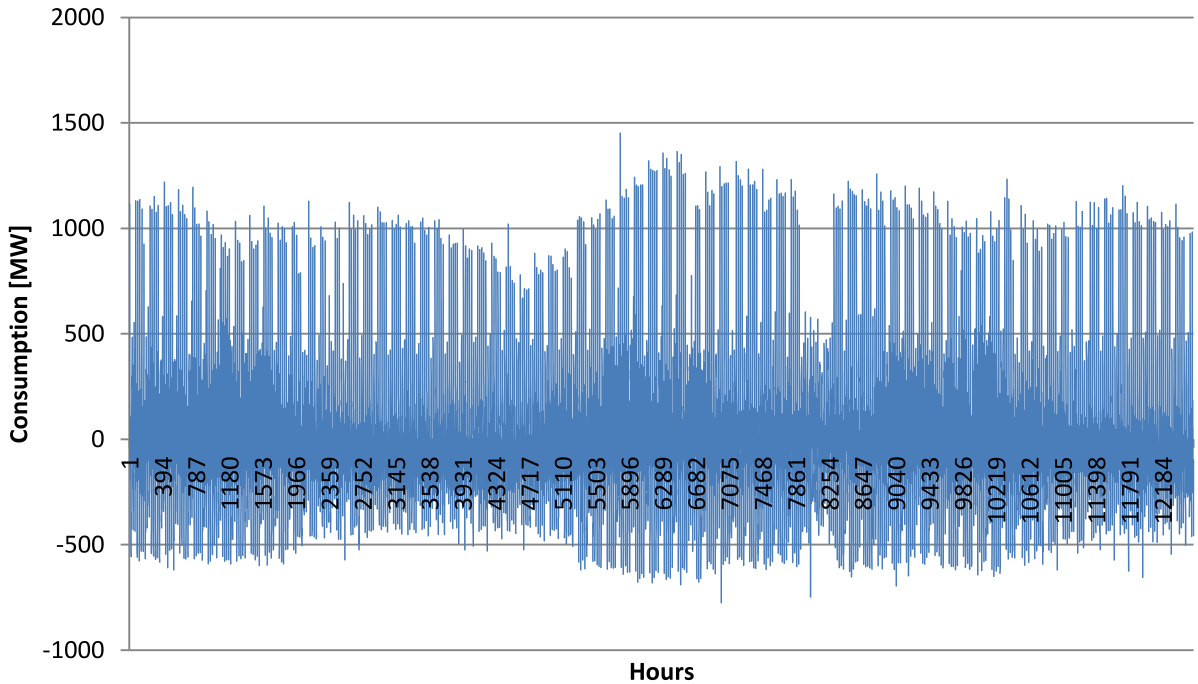

Figure 14 The change between neighbouring values (hours) of the total measure consumption in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculation .

Table 12 Descriptive statistics of the change between neighbouring values (hours) of the total measure consumption in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-0.05	-41.53	296.45	1.19	3.08	-775.62	1451.47	-149.93	110.18

The consumption day-ahead forecast is made by CEPS in order to plan the balancing of the Czech energy grid and is presented on the Figure 15 and its descriptive statistics in the Table 13.

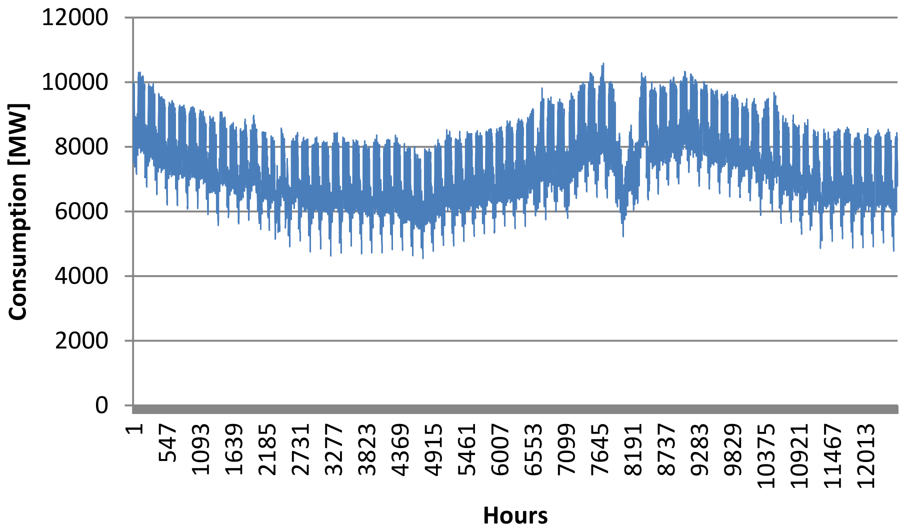

Figure 15 The consumption day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ceps.cz.

Table 13 Descriptive statistics of the consumption day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	7587.60	7607.00	1190.72	0.11	-0.68	-0.69	10581.25	6637.38	8380.13

The change between neighbouring values (hours) of the consumption's day-ahead forecast is presented on the Figure 16 and its descriptive statistics in the Table 14. These data express the step change of the consumption, which results into the decreasing or increasing trend of the system imbalance during the hour.

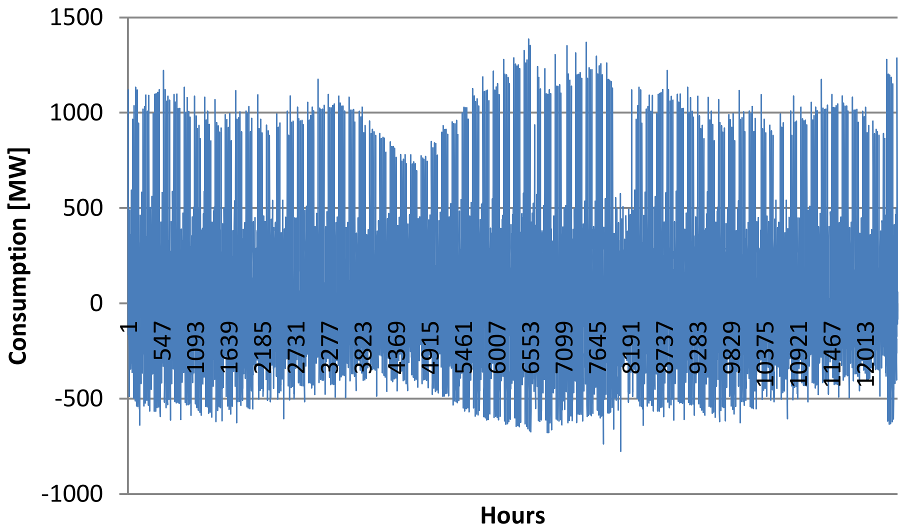

Figure 16 The change between neighbouring values (hours) of the consumption's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculation .

Table 14 Descriptive statistics of the change between neighbouring values (hours) of the consumption's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-0.05	-41.25	287.48	1.22	3.26	-776.75	1387.25	-144.25	105.75

The difference between really measured consumption and the consumption's day-ahead forecast is presented on the Figure 17 and its descriptive statistics in the Table 15. These data are one of the most important in the field of the demand variables. Any difference of the actual measured data to the planned data result into the creation of the system imbalance. This system imbalance has to be covered by the trades balancing the BRP imbalances, because each system imbalance is just the sum of the BRP imbalances.

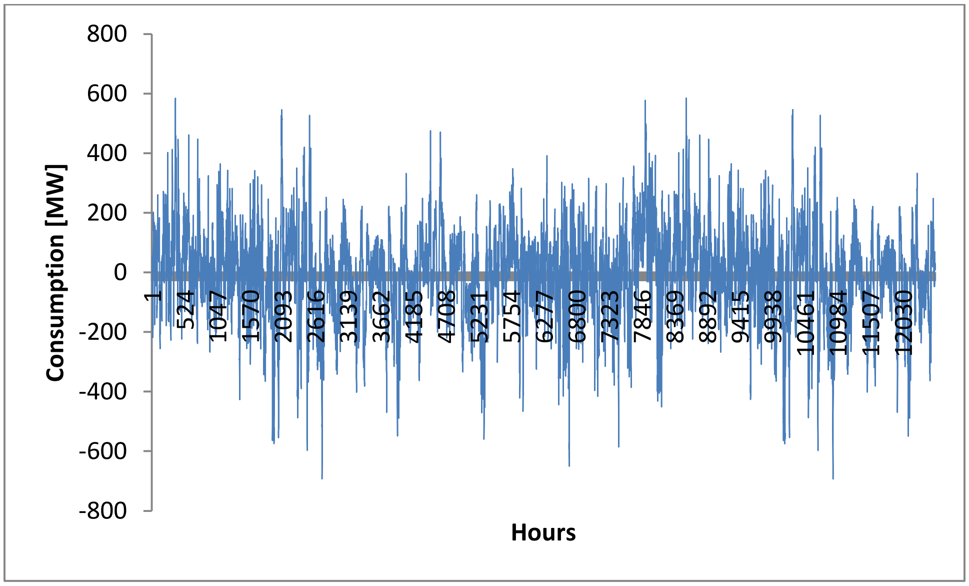

Figure 17 The difference between really measured consumption and the consumption's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 15 Descriptive statistics of the difference between really measured consumption and the consumption's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-10.56	-1.45	151.16	-0.24	1.10	-692.63	585.08	-95.09	80.81

8.1.2. Supply variables

These variables describe the supply side of the energy market. This can be described generally as the summation of all the generators or partially.

8.1.2.1. Total supply

The actual supply is also presented on the web site of the Czech TSO with a one-hour delay, and the planned value is presented on the web system of the TSO as it is the demand variable. These data are handled in the same way as the demand by taking the difference between the planned values and the actual measured. The result is the contribution to the system imbalance creation.

Total really measured supply is presented on the Figure 18 and its descriptive statistics in the Table 16. Supply data is the summation of the steam power plants, gas and combine cycle power plants, nuclear power plants, hydroelectric power plants, pumped storage plants, alternative power plants, photovoltaic power plants and wind power plants.[10]

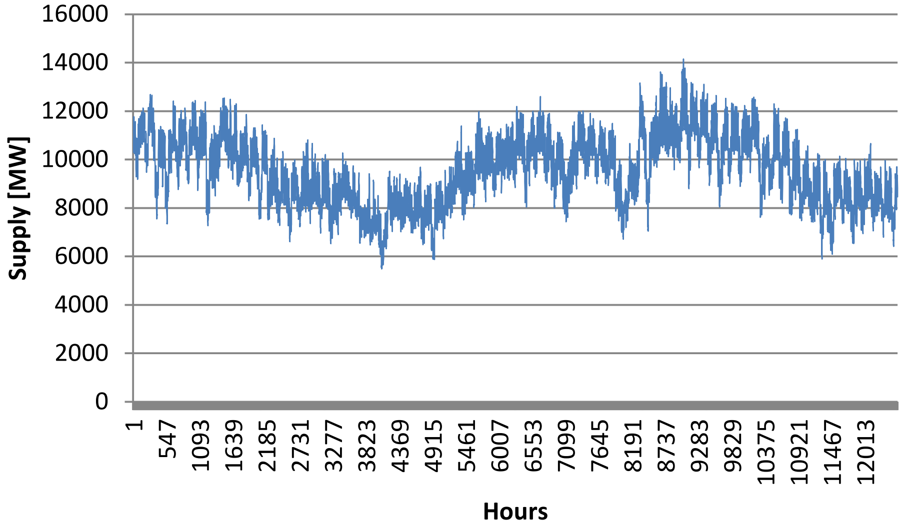

Figure 18 Total really measured supply in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ceps.cz.

Table 16 Descriptive statistics of the really measured supply in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	9576.11	9562.20	1449.41	0.00	-0.62	-0.61	14145.30	8459.65	10690.40

The change between neighbouring values (hours) of the total measure supply is presented on the Figure 19 and its descriptive statistics in the Table 17. This change of the neighbouring values is the same important as the step change of the demand, because the step change result into system imbalance intra-hour trend of the changing supply. The difference between demand and supply is that supply does not have to change the power level through the whole hour, but only at the beginning and end of the hour.

[10] http://www.ceps.cz/CZE/Data/Vsechna-data/Stranky/Vyroba.aspx

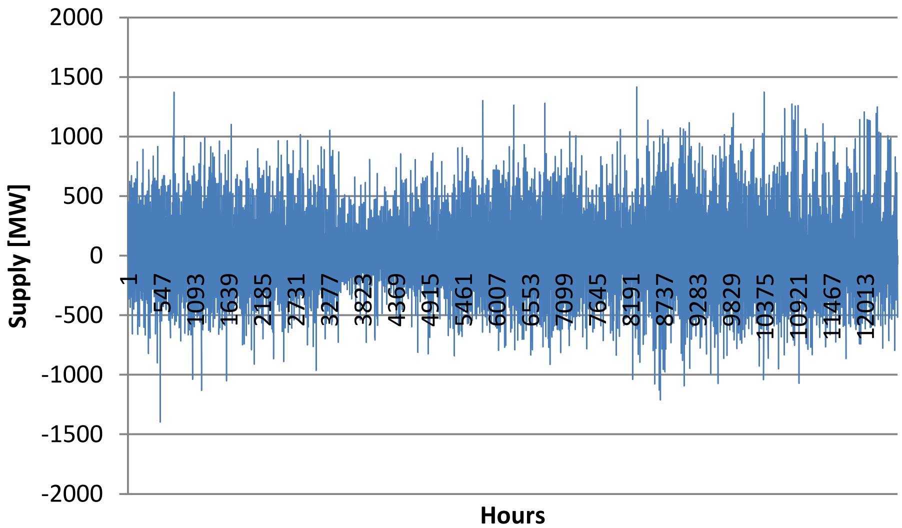

Figure 19 The change between neighbouring values (hours) of the total measure supply in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 17 Descriptive statistics of the change between neighbouring values (hours) of the total measure supply in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-0.15	-23.00	276.85	0.52	1.95	-1397.80	1416.90	-151.00	122.80

The supply day-ahead forecast is presented on the Figure 20 and its descriptive statistics in the Table 18. This forecast is again made by ČEPS in order to plan the balancing of the Czech grid.

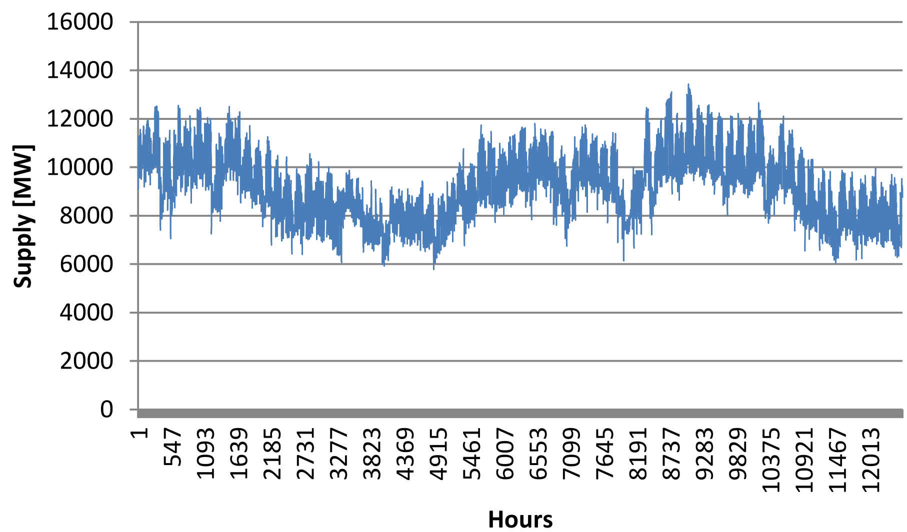

Figure 20 The supply day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ceps.cz.

Table 18 Descriptive statistics of the supply day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	9347.72	9294.00	1420.04	0.07	-0.69	-0.69	13436.00	8290.00	10439.00

The change between neighbouring values (hours) of the supply's day-ahead forecast is presented on the Figure 21 and its descriptive statistics in the Table 19.

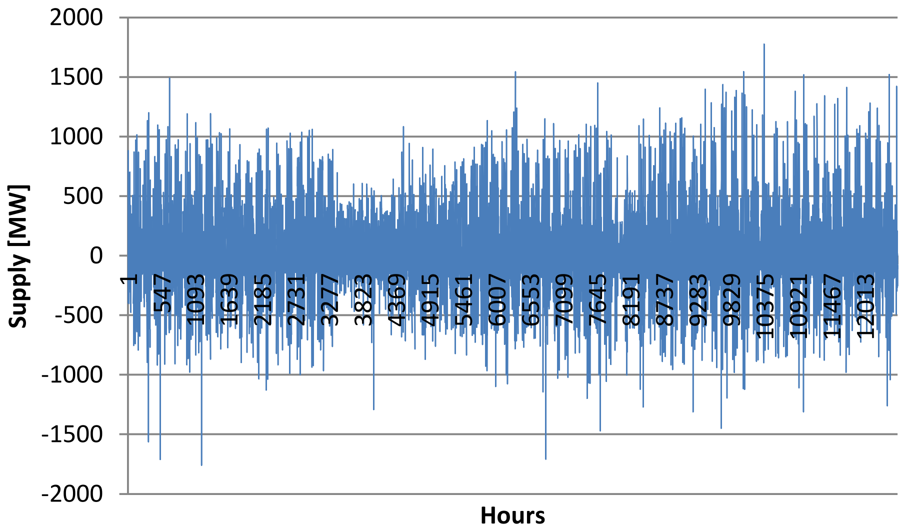

Figure 21 The change between neighbouring values (hours) of the supply's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 19 Descriptive statistics of the change between neighbouring values (hours) of the supply's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-0.06	-20.00	296.90	0.53	3.37	-1758.00	1777.00	-142.00	117.00

The difference between really measured supply and the supply's day-ahead forecast is presented on the Figure 22 and its descriptive statistics in the Table 20. This is the most important variable in the supply category as the difference between planed and actual value of the supply result into the creation of the system imbalance.

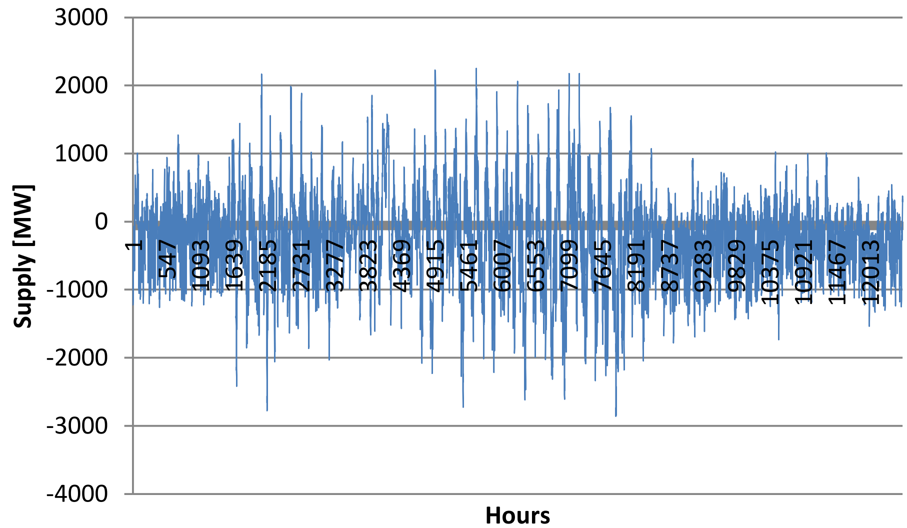

Figure 22 The difference between really measured supply and the supply's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 20 Descriptive statistics of the difference between really measured supply and the supply's day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-228.39	-192.40	640.69	-0.07	1.03	-2859.30	2248.00	-581.70	119.35

8.1.2.2. RES electricity supply

I aim at the supply from RES, the power from which cannot be controlled and which are very hard to forecast. Here, I use the actual production and forecast presented at 01:00 for the next day[11][12]. The RES power generation used in my dissertation are the German wind power, German photovoltaic power and Czech photovoltaic power. I assume that the strong connection

[11]The day-ahead market closes at 11:00 am for the next day, so the last available data at the close time is the forecast made at 01:00 am.

[12] The forecast is obtained from the Thomson Reuters database, where the forecast is based on the EC model. For more information see: [36]

between the German and Czech power markets leads to the fact that the Czech system imbalance is influenced by the imbalance in the supply from German RES. It is necessary to filter the photovoltaic generation variables from the night hours with zero generation. Information about the German balancing market can be found in [18] or [23].

The really measured supply of photovoltaic power plants in the Czech Republic is presented on the Figure 23 and its descriptive statistics in the Table 21. These data are filtered in order to discard the zero values of the photovoltaic power production as these values have no information usable for the forecast model.

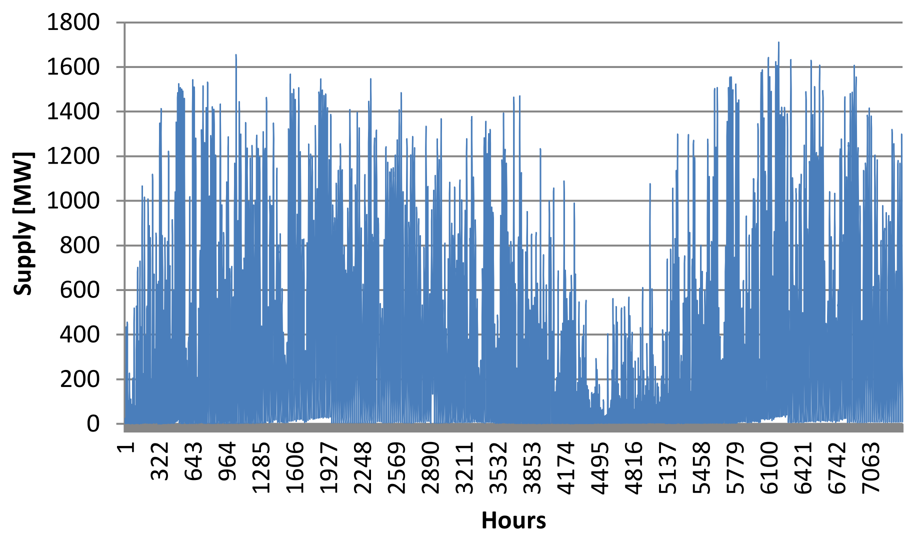

Figure 23 The really measured supply of photovoltaic power plants in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ceps.cz.

Table 21 Descriptive statistics of the really measured supply of photovoltaic power plants in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skewness	Kurtosis	Min	Max	25% quartile	75% quartile
7374	431.09	294.39	426.18	0.86	-0.38	-0.38	1712.23	51.63	727.38

The difference between really measured supply of photovoltaic power plants and the supply of photovoltaic power plants day-ahead forecast is presented on the Figure 24 and its descriptive statistics in the Table 22. These data are very important as the photovoltaic power production is very hard to forecast and the plan is very often significantly different from the actual data. It depends mainly on the cloud coverage, which is impossible to forecast day-ahead with 100% accuracy. The most of the system imbalances created by incorrect plan of the production in the Czech Republic come from these types of sources (photovoltaic power plants).

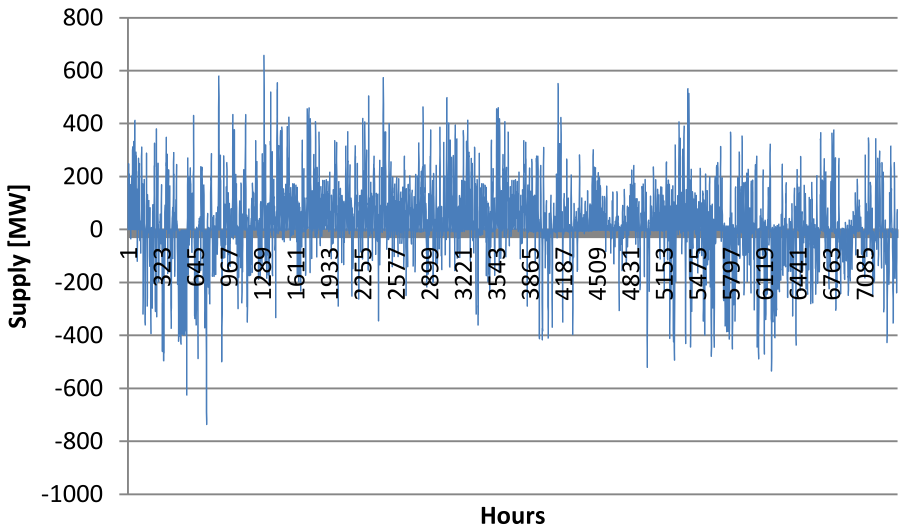

Figure 24 The difference between really measured supply of photovoltaic power plants and the supply of photovoltaic power plants day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 22 Descriptive statistics of the difference between really measured supply of photovoltaic power plants and the supply of photovoltaic power plants day-ahead forecast in the Czech Republic in the date from 29 January 2014 to 30 June 2015.

Source: own calculation

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
7406	22.59	10.05	140.65	-0.31	2.21	-737.38	657.48	-15.93	91.87

The really measured supply of photovoltaic power plants in the Germany is presented on the Figure 25 and its descriptive statistics in the Table 23. These data are filtered in order to discard the zero values of the photovoltaic power production as these values have no information usable for the forecast model. It is interesting to compare the level of the production of the photovoltaic power plant in Germany and in Czech Republic, as in Germany, there are more than ten times higher production of the photovoltaic power plant compared to the Czech Republic.

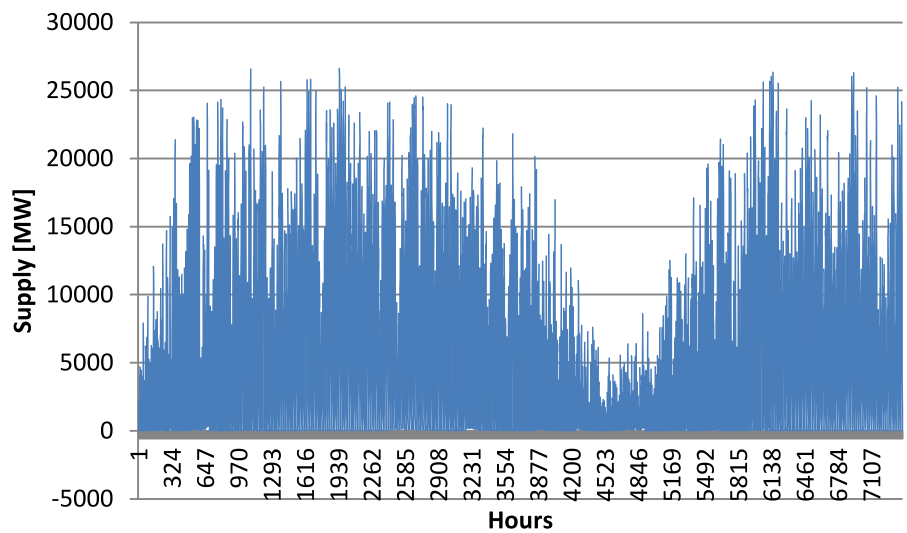

Figure 25 The really measured supply of photovoltaic power plants in the Germany in the date from 29 January 2014 to 30 June 2015. Source: Thompson Reuters.

Table 23 Descriptive statistics of the really measured supply of photovoltaic power plants in the Germany in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
7413	6961.37	4975.52	6586.56	0.81	-0.39	-2.51	26631.05	1072.78	11536.38

The difference between really measured supply of photovoltaic power plants and the supply of photovoltaic power plants day-ahead forecast in Germany is presented on the Figure 26 and its descriptive statistics in the Table 24. Here I work with hypothesis that change of the system imbalance in the Germany created by incorrect forecast of the photovoltaic power plant production in Germany influence the system imbalance in the Czech Republic.

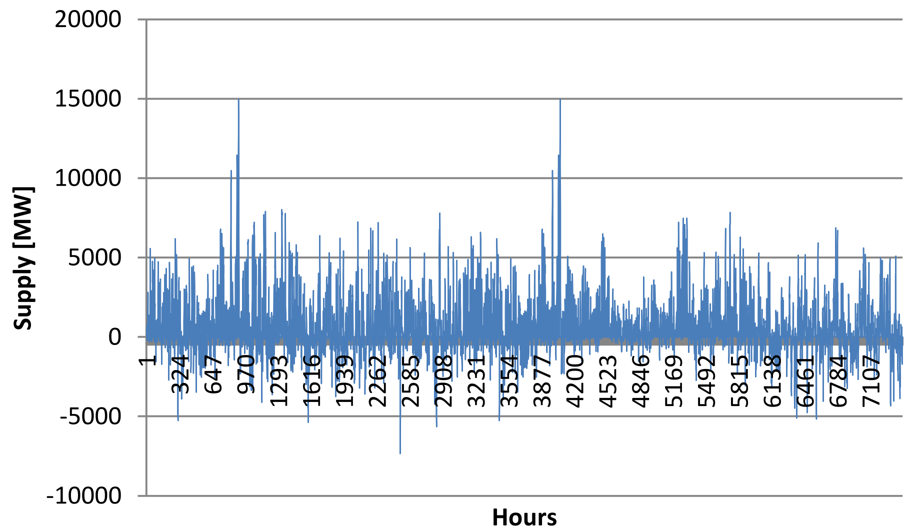

Figure 26 The difference between really measured supply of photovoltaic power plants and the supply of photovoltaic power plants day-ahead forecast in the Germany in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 24 Descriptive statistics of the difference between really measured supply of photovoltaic power plants and the supply of photovoltaic power plants day-ahead forecast in the Germany in the date from 29 January 2014 to 30 June 2015.

Source: own calculations

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
7426	701.10	202.18	1810.84	1.44	5.71	-22225.74	14950.29	-178.50	1421.22

The really measured supply of wind power plants in the Germany is presented on the Figure 27 and its descriptive statistics in the Table 25. Here I present only data of the wind power plant in Germany as the production of the wind power plant in the Czech Republic in not so important compared to the Germany wind power plant or Czech Republic photovoltaic power plants.

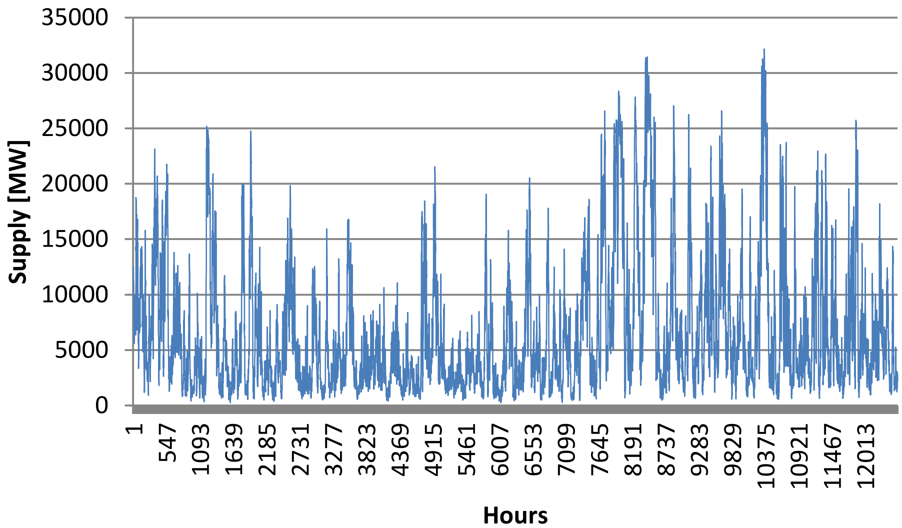

Figure 27 The really measured supply of wind power plants in the Germany in the date from 29 January 2014 to 30 June 2015. Source: Thompson Reuters.

Table 25 Descriptive statistics of the really measured supply of wind power plants in the Germany in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	6590.82	4481.49	5944.02	1.61	2.32	-1.00	32160.96	2383.11	8814.62

The change between neighbour values (hours) of supply of wind power plants in the Germany is presented on the Figure 28 and its descriptive statistics in the Table 26. In this data, I analyses the step change of the wind power plant production in Germany as this value changes very often as is even more difficult to forecast than the photovoltaic power plant. From that reason the sudden change of the wind power plant production results in significant system imbalance creation.

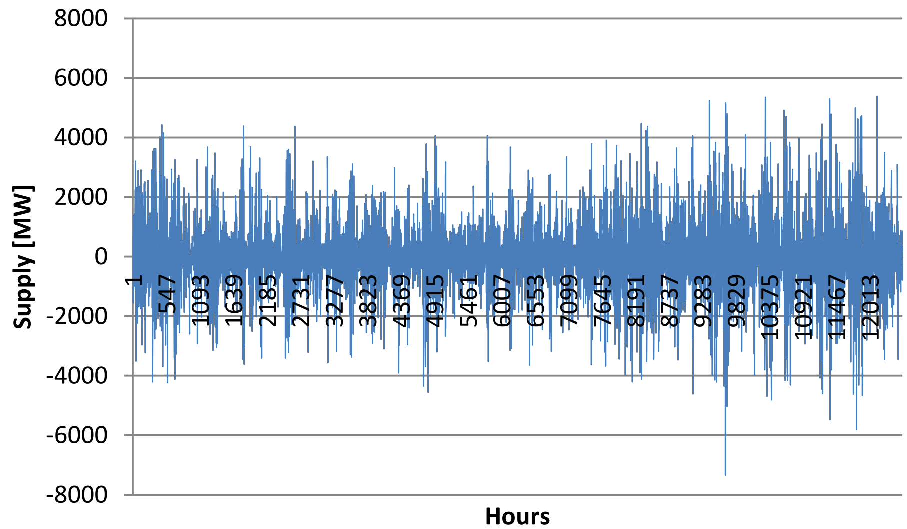

Figure 28 The change between neighbour values (hours) of supply of wind power plants in the Germany in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 26 Descriptive statistics of the change between neighbour values (hours) of supply of wind power plants in the Germany in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-0.73	-13.92	1036.18	0.05	3.05	-7332.60	5386.21	-479.25	471.04

The difference between really measured supply of wind power plants and the supply of wind power plants day-ahead forecast in Germany is presented on the Figure 29 and its descriptive statistics in the Table 27. These data are used due to the hypothesis that system imbalance in the Germany influence the system imbalance in the Czech Republic.

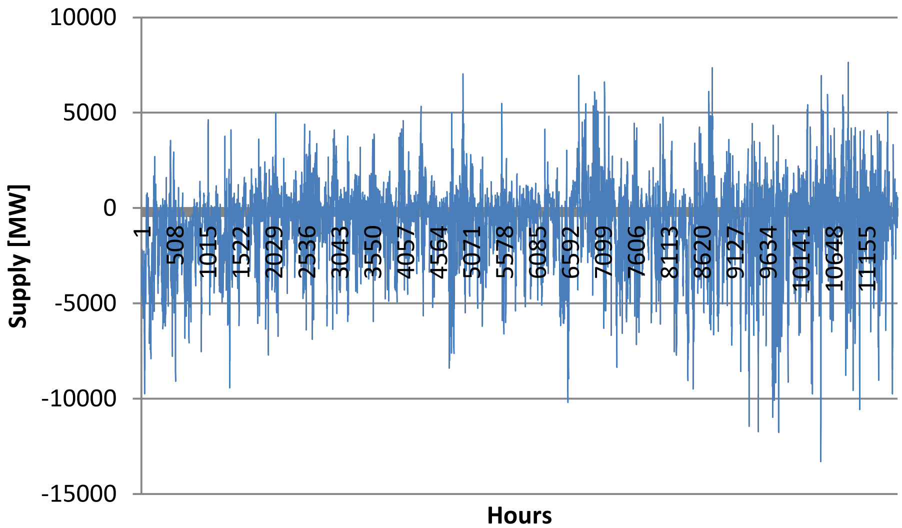

Figure 29 The difference between really measured supply of wind power plants and the supply of wind power plants day-ahead forecast in the Germany in the date from 29 January 2014 to 30 June 2015. Source: own calculation.

Table 27 Descriptive statistics of the difference between really measured supply of wind power plants and the supply of wind power plants day-ahead forecast in the Germany in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
11639	-881.32	-521.39	2121.66	-0.76	2.26	-13307.37	7640.61	-1871.86	304.30

8.1.3. Variable capturing market participants' behaviour

This variable captures the behaviour of all the market participants and their own personal forecasts of the future development.

8.1.3.1. Intraday market price

The intraday market plays the role of the last chance to balance the BRP position and make a speculation on the system imbalance. When the system imbalance is significantly negative (there is a shortage of energy), the price on the intraday market climbs up and does the opposite for a positive system imbalance. Keeping in mind the hourly average price, we can observe the behaviour of the market participants and speculate in the same direction (direction of the BRP imbalance). The closing time of the intraday market is one hour before delivery, so there is enough time to modify the amount of generated electricity.

The intraday price of the electricity is presented on the Figure 30 and its descriptive statistics in the Table 28.

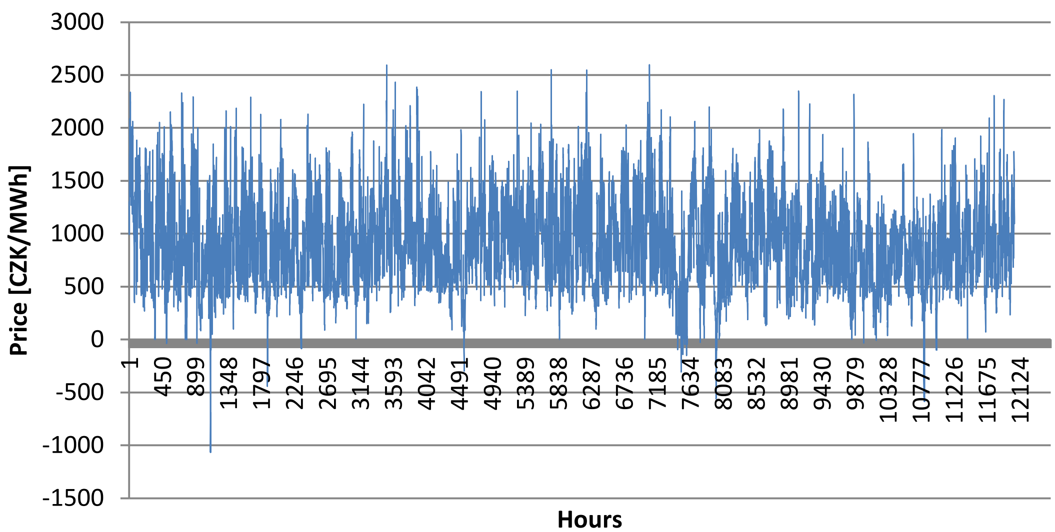

Figure 30 The intraday price of the electricity in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ote-cr.cz.

Table 28 Descriptive statistics of the intraday price of the electricity in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12057	887.09	850.99	418.74	0.37	0.27	-1066.35	2596.21	573.33	1155.72

8.1.3.2. Balancing market volume

This is the market where the TSO buys the balancing power for the next hour (closing time is 30 minutes before delivery). Thus, the amount and type of regulation energy (upward or downward) carries the information of the TSO system imbalance forecast for the next hour. It is again necessary to filter the balancing market volume from the hours without any trade.

The volume of the balance market is presented on the Figure 31 and its descriptive statistics in the Table 29. There is presented both upward and downward regulation energy traded on the balancing market.

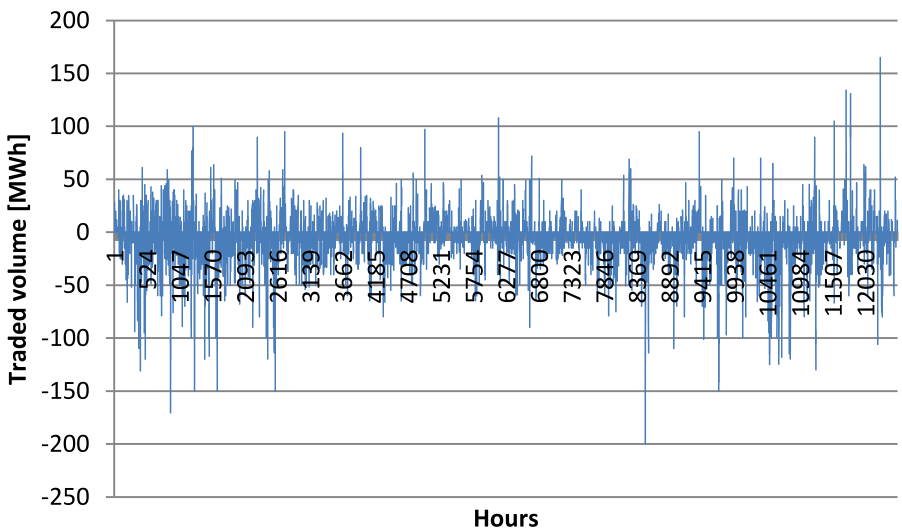

Figure 31 The volume of the balance market in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ote-cr.cz.

Table 29 Descriptive statistics of the volume of the balance market in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-3.41	0.00	18.31	-1.70	15.20	-1861.11	165.00	0.00	0.00

The volume of the downward balance market is presented on the Figure 32 and its descriptive statistics in the Table 30. These data are filtered to discard upward regulation energy and mainly the hours, where no regulation energy was traded – these are the most hours, where is not any trade made on balancing market. There is only 3089 hours, where the downward regulation was traded.

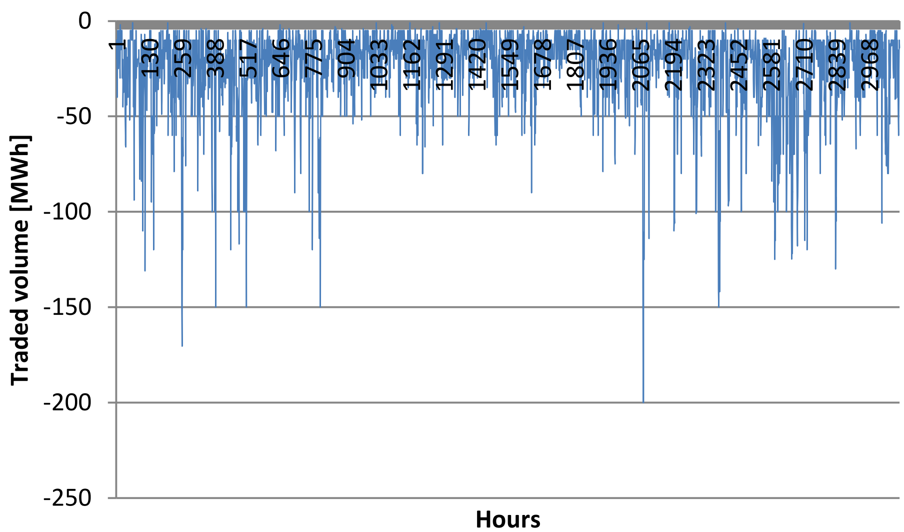

Figure 32 The volume of the downward balance market in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ote-cr.cz.

Table 30 Descriptive statistics of the volume of downward the balance market in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
3089	-24.22	-19.00	21.91	-2.52	9.03	-1873.41	-1.00	-30.00	-10.00

The volume of the upward balance market is presented on the Figure 33 and its descriptive statistics in the Table 31. These data are filtered to discard downward regulation energy and again mainly the hours, where no regulation energy was traded. There is only 1680 hours, where the upward regulation was traded.

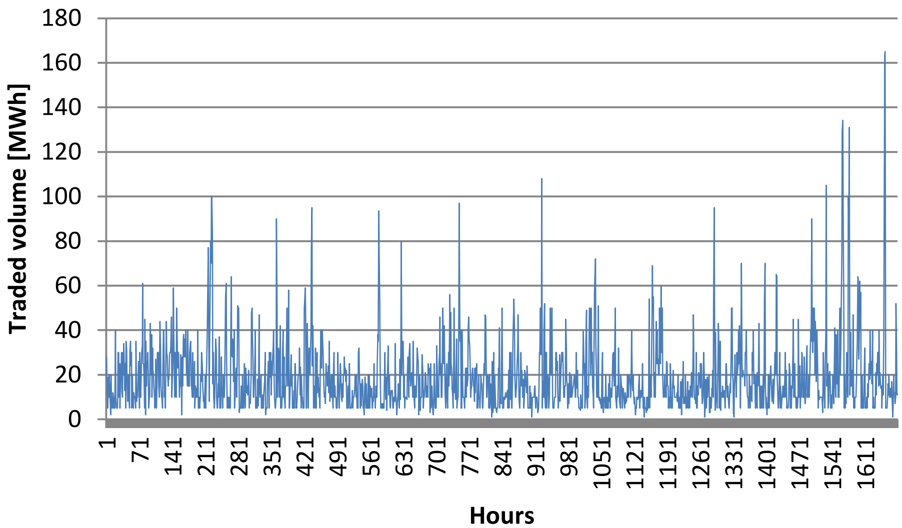

Figure 33 The volume of the upward balance market in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ote-cr.cz.

Table 31 Descriptive statistics of the volume of upward the balance market in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
1680	18.98	15.00	16.50	2.87	14.17	1.00	165.00	10.00	25.00

8.1.3.3. Day-ahead market price

The spot day-ahead market price reflects the position of the electricity generators. When the spot price is high, most of the power sources are at the maximum technical level of generation and there is not enough space to increase the amount of generated electricity. In a situation where a negative system imbalance occurs, the power sources are not able to increase their generation and lower the system imbalance. The system imbalance is then more stable. The opposite situation exists for a low spot price, which leads to generation at the minimum level and an inability to decrease the amount of generated electricity.

The day-ahead price of the electricity is presented on the Figure 34 and its descriptive statistics in the Table 32. The day-ahead spot market closes at 11:00 and publishes results at 11:40 previous day to the day of the delivery.[13]

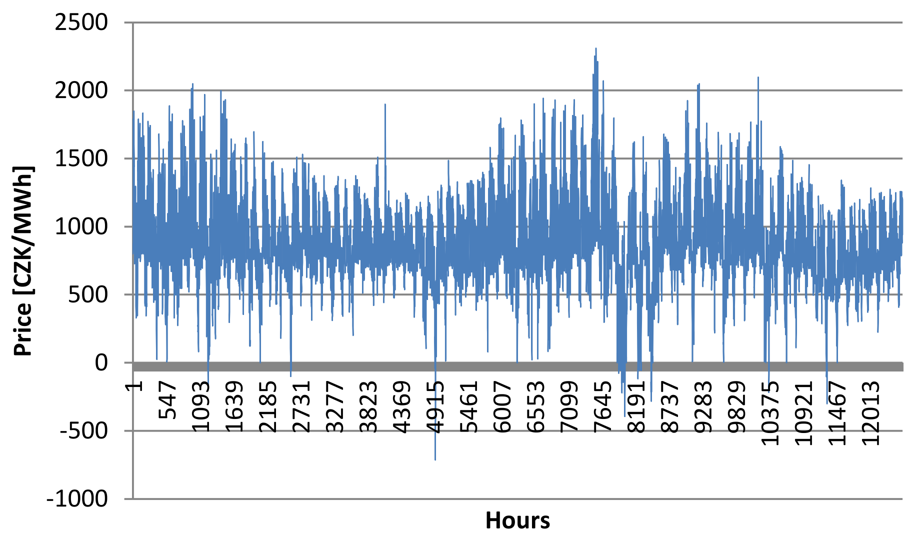

Figure 34 The day-ahead price of the electricity in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ote-cr.cz.

[13] www.ote-cr.cz

Table 32 Descriptive statistics of the day-ahead price of the electricity in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	879.94	861.90	330.45	0.07	0.69	-713.86	2310.14	685.39	1081.64

8.1.3.4. Cross-borders physical flows

Cross-borders physical flow presents the export and import status of the country to surrounding countries. Change of the flow can result in to the change of the system imbalance. Cross-borders physical flow is also presented on the web site of the Czech TSO with a one-hour delay, and the planned value is presented on the web system of the TSO. These data are handled by taking the difference between the planned values and the actual measured. The result is the contribution to the system imbalance creation.

The cross-borders physical flow is presented on the Figure 35 and its descriptive statistics in the Table 33. These data are the sum of each individual cross-border. For Czech Republic, surrounding areas (TSO's) are:

- 50 HZt (Germany)
- TenneT (Germany)
- APG (Austria)
- SEPS (Slovakia)
- PSE (Poland)

Demonstration of the cross-border flows is presented in the Figure 36.

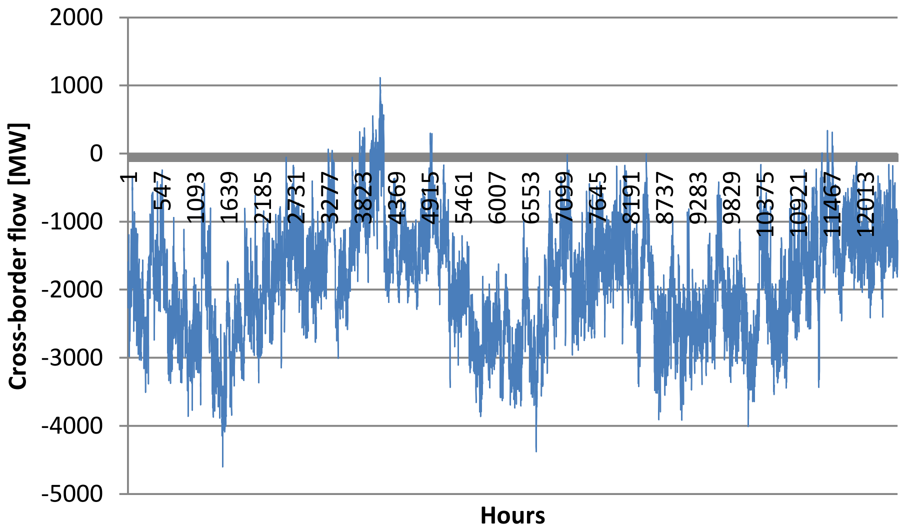

Figure 35 The cross-borders physical flow in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ote-cr.cz.

Table 33 Descriptive statistics of the cross-borders physical flow in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	-1873.41	-1861.11	827.18	0.08	-0.29	-4604.28	1114.74	-2485.65	-1282.35

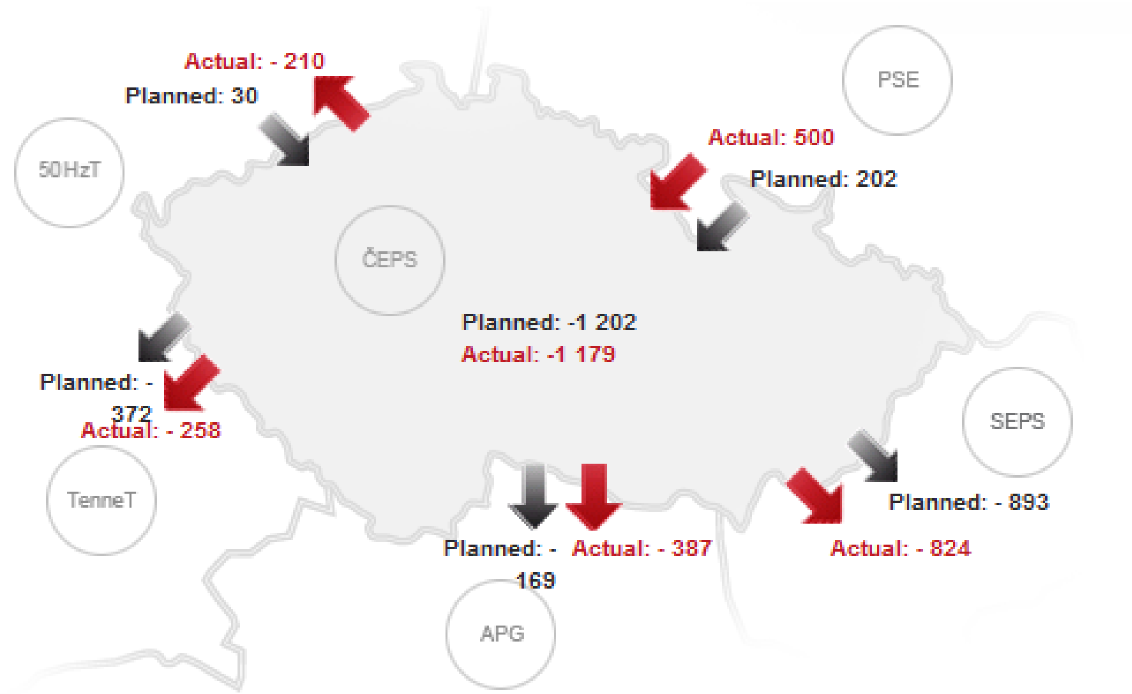

Figure 36 Demonstration of the cross-border flows. Source: www.ceps.cz

The change between neighbouring values (hours) of the cross-borders physical is presented on the Figure 37 and its descriptive statistics in the Table 34. Change between neighbouring values of the cross-border flows are often the result of the trades made by market participants. These trades can be made to hedge their portfolios, arbitration trades or speculate to the BRP imbalance opposite to the system imbalance.

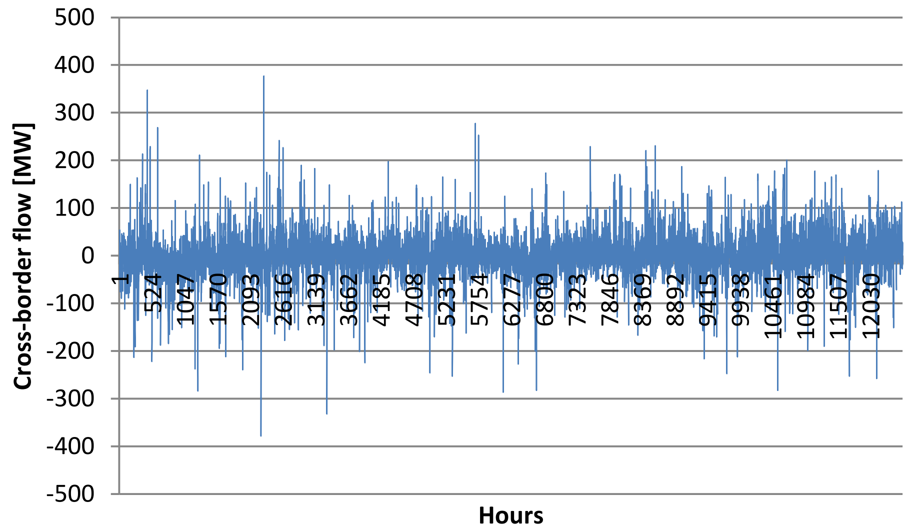

Figure 37 The change between neighbouring values (hours) of the cross-borders physical in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: www.ote-cr.cz.

Table 34 Descriptive statistics of the change between neighbouring values (hours) of the cross-borders physical in the Czech Republic in the date from 29 January 2014 to 30 June 2015. Source: own calculations.

Hours	Average	Median	Std. Deviation	Skew -ness	Kurtosis	Min	Max	25% quartile	75% quartile
12551	1.88	1.53	41.80	-0.18	7.13	-378.38	376.84	-16.93	20.83

All the descriptive statistics and the review of the all data inputs are displayed in the Table 35.

Table 35 Descriptive statistics of the inputs. IMP = intraday market price, SDAMP = spot day-ahead market price, BMP = balancing market price, Diff = difference between reality and forecast, AVD = adjacent value differences. Source: own calculation.

	Number of samples	Average	Median	Stand. Deviation	Skew-ness	Kurtosis	Minimum	Maximum	25% quartile	75% quartile
IMP	12057	887.1	851.0	418.7	0.372	0.274	-1066.4	2596.2	573.3	1155.7
SDAP	12551	879.9	861.9	332.8	0.068	0.667	-713.9	2310.1	685.1	1082.9
BMP+	1680	19.0	15.0	16.5	2.875	14.167	1.0	165.0	10.0	25.0
BMP-	3089	-24.2	-19.0	21.9	-2.523	9.030	-200.0	-1.0	-30.0	-10.0
BMP	12551	-3.4	0.0	18.2	-1.854	14.727	-200.0	134.2	0.0	0.0
photovoltaic CZ real.	7374	431.09	294.39	426.18	0.86	-0.38	-0.38	1712.23	51.63	727.38
photovoltaic CZ diff	7406	22.59	10.05	140.65	-0.31	2.21	-737.38	657.48	-15.93	91.87
photovoltaic DE real.	7413	6961.37	4975.52	6586.56	0.81	-0.39	-2.51	26631.05	1072.78	11536.38
photovoltaic DE diff	7426	701.10	202.18	1810.84	1.44	5.71	-22225.7	14950.29	-178.50	1421.22
wind DE real.	12551	6590.8	4481.5	5985.0	1.598	2.264	260.6	32161.0	2384.7	8847.3
wind DE change	12551	-0.7	-13.9	1038.0	0.051	3.067	-7332.6	5386.2	-480.2	471.9
wind DE diff	11639	-881.3	-521.4	2121.7	-0.763	2.263	-13307.4	7640.6	-1871.9	304.3
Total supply real.	12551	9576.1	9562.2	1448.1	-0.027	-0.611	5491.4	14145.3	8498.6	10719.4
Total supply change	12551	-0.1	-23.0	277.2	0.512	1.931	-1397.8	1416.9	-151.1	123.1
Total consumption – real	12551	7698.0	7708.8	1237.0	0.155	-0.601	4617.6	10855.3	6737.8	8528.7
Total consumption. Change	12551	-0.1	-41.5	297.0	1.185	3.075	-775.6	1451.5	-149.9	110.8

export-import real	12551	-1873.4	-1861.1	827.7	0.109	-0.264	-4604.3	1114.7	-2500.9	-1304.2
export-import diff	12551	1.9	1.5	41.9	-0.170	7.223	-378.4	376.8	-17.1	20.5
Total supply - plan	12551	9347.7	9294.0	1415.9	0.052	-0.686	5786.0	13436.0	8328.0	10467.0
Total supply - plan change	12551	-0.1	-20.0	297.0	0.522	3.319	-1758.0	1777.0	-142.0	118.0
Total supply - plan minus real	12551	-228.4	-192.4	645.7	-0.070	0.997	-2859.3	2248.0	-584.7	123.8
Total consumption - plan	12551	7587.6	7607.0	1192.1	0.103	-0.691	4539.5	10581.3	6651.4	8402.4
Total consumption - plan change	12551	-0.05	-41.25	287.48	1.22	3.26	-776.75	1387.25	-144.25	105.75
Total consumption - plan minus real	12551	-10.56	-1.45	151.16	-0.24	1.10	-692.63	585.08	-95.09	80.81

8.2. Correlation analysis

In this chapter, I count the correlation analysis of the presented exogenous variables. At first I count the autocorrelation coefficient of the system imbalance. From the Figure 38 I can see, that first few values of the autocorrelation indicate very strong autocorrelation, which should lead to involve lagged value of the system imbalance into input variables of the future forecasting model. Namely the first three values are: 0.78 for the lag of one hour, 0.52 for the two hours lag and 0.34 for three hours. I can therefore involve lagged value of the system imbalance into input variables of the future forecasting model. (Lagged of one hour or two hours, if the one hour value would not be available at the time of forecast).

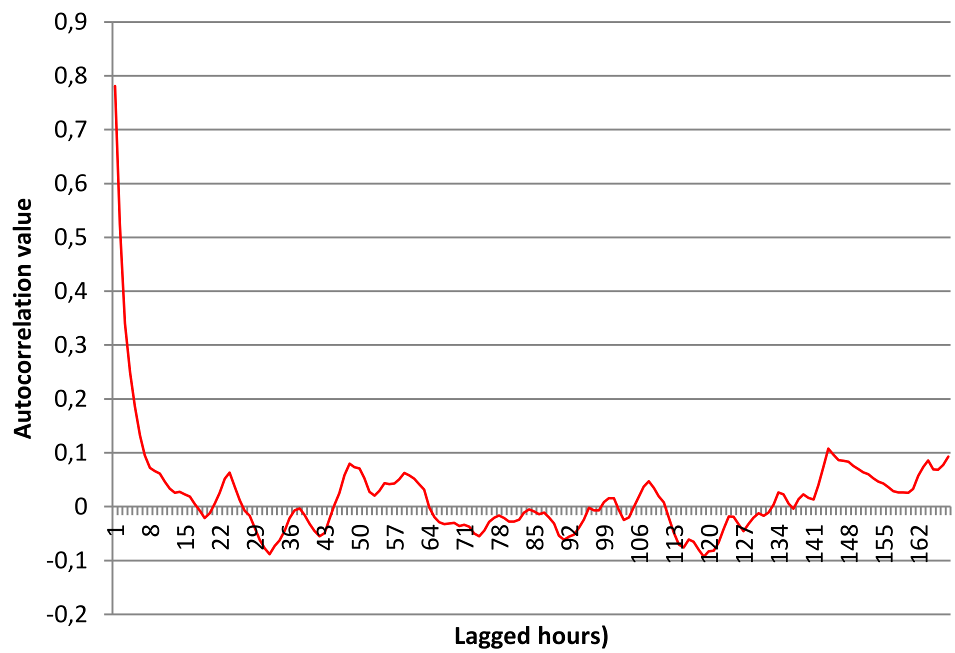

Figure 38 Autocorrelation of the system imbalance with lag between 1 and 176 hours (1 week). Source: own calculation.

In the Table 36 are presented the correlation analysis of the system imbalance and the other exogenous variables. This analysis does not suggest the usage of the German RES (Renewable energy sources) power generation, as the correlation values are very low. On the other hand, the inputs concerning Czech PV (Photovoltaic) differs between planed and actual measured value are presented with very high correlation values. From the other inputs, the best results were achieved by the IMP, BM (also BMP+ and BMP-) and the difference between planed and actual measured value of the difference between export and import.

Table 36 Correlation analysis of the system imbalance and the other exogenous variables. Source: own calculation.

Lag	**0 hour**	**1 hour**	**2 hours**	**Lag**	**0 hour**	**1 hour**	**2 hours**
IMP	-0.429	-0.496	-0.536	wind DE real.	0.067	0.062	0.058
SDAP	-0.174	-0.161	-0.137	wind DE change	-0.022	-0.026	-0.020
BMP+	-0.328	-0.397	-0.276	wind DE diff	-0.013	-0.002	0.001
BMP-	-0.384	-0.502	-0.407	Total supply real.	-0.114	-0.109	-0.093

BMP	-0.477	-0.556	-0.519	Total supply change	-0.061	0.021	0.079
photovoltaic CZ real.	0.202	0.184	0.144	Total consumption – real	-0.140	-0.125	-0.105
photovoltaic CZ diff	-0.443	-0.399	-0.297	Total consumption. Change	-0.080	0.055	0.074
photovoltaic DE real.	0.069	0.062	0.051	export-import real	0.005	0.019	0.019
photovoltaic DE diff	-0.095	-0.096	-0.090	export-import diff	0.575	0.380	0.236

Generally, the correlation coefficients are not statistically very interesting and therefore I suggest using interval distribution of the data along with the basic point forecast. Distribution into intervals decreases the risk arising from the money lost caused by the incorrect forecast or choosing too high speculation value of the BRP imbalance to a too small value of the system imbalance, which would lead to changing of the direction of the system imbalance (caused by our intervention). For the successful speculation on the opposite direction of the BRP imbalance to the system imbalance, I do not need to know exact value of the system imbalance – just the interval, in which is system imbalance probably lie. For our purposes, the distribution into 2 and 5 intervals were chosen.

Two intervals data distribution result only in dividing the system imbalance into positive and negative values.

Distribution of the input data and system imbalance into 5 intervals brings several benefits. At first, there is the middle interval, which is very risky for the speculation (risk of the changing of the direction of the system imbalance caused by our intervention). Both directions are further divided into two intervals, which can define two speculation values for minimizing of the risk and maximization of the revenues. More than 5 intervals makes the solution very complicated, as the inputs are not capable to define exactly all the intervals and the results of the successful forecast are worse than for 5 intervals. Interval distribution is described in detail in the following chapter.

9. Methodology

9.1. Interval data distribution

As I stated before, I do not forecast the exact value of the system imbalance, but only its interval. Two types of interval distributions have been chosen: two and five-interval distributions. The five-interval distribution was chosen for setting of the zero intervals eliminating the speculation, which are risky and 2 intervals in each direction, which reduce the risk consequent from speculation. More intervals could not be used as the exogenous variables cannot divide the system imbalance forecast into more intervals with the sufficient accuracy. A two-interval distribution was chosen as the benchmark to the five-interval distributed data.

In two-interval distribution, I set the boundary of the system imbalance on the zero value. This boundary is a logical choice as we try to distinguish forecast between shortage (in-sufficient energy in the grid) and surplus (too many energy in the grid), which are separated by the zero value of the system imbalance.

For five-interval distribution, I marked the intervals with numbers -2, -1 for negative imbalance, 0 for the middle interval and 1 and 2 for positive imbalance. For the middle interval, I chose values between -20 and 20 MW. The values of the boundaries are based on the expert knowledge of the author of the thesis. These boundaries were set in order to avoid the risk of changing the direction of the system imbalance by speculation on BRP imbalance. Each BRP imbalance causes the system imbalance in the same direction[14]. I chose values for defining the extreme values of 10 % (first quartile) and thus the limits are -77 and 104 MW respectively, for values of the intervals separating the positive and negative imbalance. This decision is again motivated by the effort of the risk reduction as was explained above. The higher the value of the system imbalance is, the larger the speculation on the BRP imbalance can be made, because of the risk of changing the direction of the system imbalance. Intervals of the system imbalance are thus defined:

- Interval no. -2: <-∞, -77)
- Interval no. -1: <-77, -20)

[14] E.g. we have system imbalance in surplus 30 MW and decide to speculate on the opposite direction of the BRP imbalance achieving position of the shortage -10 MW. The resulting system imbalance is then surplus 20 MW (30 – 10 = 20), and BRP is paid for achieving opposite direction of the BRP imbalance to the system imbalance. But If we had system imbalance only 5 MW in surplus with the same speculation -10 MW in shortage of BRP imbalance, the resulting system imbalance would be -5 MW in shortage (5 – 10 = -5). The BRP then pays for achieving the same direction of the BRP imbalance to the system imbalance.

- Interval no. 0: <-20, 20)
- Interval no. 1: <20, 104)
- Interval no. 2: <104, ∞)

The individual input data differ in quantity. This is due to the need for removing the data with zero real trades by business data and the photovoltaic data. These data were removed for hours with zero generation – these are all hours through night, which data are irrelevant for the forecast of the system imbalance. The most important are the boldfaced values (Annex A and B) which are indicating the accuracy of the individual input forecast of the system imbalances' interval in both absolute and relative terms. This accuracy is calculated as the number of successfully forecasted system imbalance intervals divided by the number of data samples. First are the numbers of hours, where the interval system imbalance provides relevant interval input data. Furthermore, the tables show the precision with the usage of 5 intervals, which determines the correct direction of the imbalance (if the imbalance is negative, the interval input variables become -2 or -1, and vice versa for positive imbalance). The last bold figure shows the accuracy of correctly stated direction of the system imbalance.

I used the mathematical tool Wolfram Mathematica, which enabled setting such limits that cause the highest possible accuracy of the model (in the terms of both successfully forecasted system imbalance intervals and the system imbalance direction) to optimize the interval limits. This means that I maximized the number of cases, where the interval of the system imbalance of the given limits are the same as the interval input variables of other input factors attributable to this. I used the simulated annealing and differential evolution algorithms for the optimization [21, 22].

The process of the optimization starts with the creation of the mapping function, which assign the corresponding number of the interval to the actual data. Then this function is applied on the data of the system imbalance, which transfer all exact system imbalance values into intervals. After distribution the system imbalance into intervals, the mapping function is applied on the data of the individual exogenous input variable (in the theoretical way). So the data of the exogenous input variable are divided into intervals by the function, which has not determined the interval boundaries yet. Then, there is defined the maximization of the function, which for each data point equal 1, when the interval of the system imbalance equals to the interval of the exogenous input variable (still in theoretical way). The maximization process is applied on the sum of the function results for all of the data points. The last step of the optimization is the application of the function "NMaximize", which according to the simulated annealing and differential evolution algorithms, tries to find out the best interval boundaries for the exogenous input variable to maximize the result of the maximization function mentioned above. This process of optimization is repeated for each exogenous input variable. For better understanding of the procedure, the whole Wolfram Mathematica code is presented in the Annex. C.

The interval boundaries resulting from the optimization were then adjusted in order to get the distribution close to the normal distribution of the intervals, but do not significantly reduce the accuracy of the forecast. The number of correctly stated values should be maximized to achieve higher accuracy.

The optimization can be defined as:

$$\max_{a_i} \sum_{i=1}^{T} a_i \times b_i \tag{43}$$

for each exogenous variable.

Where T is the number of hours of input data,

$a = (a_1, a_2, a_3, a_4, a_5)$ and $a_j = 1$ when the interval input variable of system imbalance is assigned to the interval j, otherwise $a_j = 0; j \in \{1,2,3,4,5\}$,

$b = (b_1, b_2, b_3, b_4, b_5)$ and $b_j = 1$ when the interval input variable of other input factors is assigned to the interval j, otherwise $b_j = 0; j \in \{1,2,3,4,5\}$.

9.2. Model description

The model for forecasting intervals of the system imbalance is based on the interval distribution of the exogenous inputs described above. The model can be described as the sum of the vector interval´s multiplications of the system imbalance forecast based on each exogenous variable and the percentage accuracy of the successful forecast of the exogenous variable. Only system imbalance itself lagged by two hours is multiplied by one, because of its strong autocorrelation value, which is 0.52.

All the exogenous variables based on the prices and volumes of the realized trades are not lagged. This can be done because of the time lag between closing of the trading for the hour and the beginning of the hour (delivery). This lag is one hour for the intraday market and half of an hour for the balancing market. (For the day-ahead market the lag is minimum of 12 hours).

All the other exogenous variables are lagged by two hours (newer data are not available at the time). The model can be described as:

$$SI_t = SI_{t-2} + \alpha_{i,p} X_t^p + \alpha_{i,r} X_{t-2}^r \tag{44}$$

Where SI_t is the interval value of the system imbalance forecast at the time t and SI_{t-2} is the real (measured) system imbalance interval value at the time $t-2$. X_t^p are system imbalance interval forecasts based on exogenous variables describing realized trades on day-ahead, intraday and balance markets (volumes and prices) at the time t. X_{t-2}^r are system imbalance interval forecasts based on the rest of the exogenous variables (RES, consumption, supply, cross-border) at the time $t-2$. α_i is the percentage accuracy of the successfully forecasted system imbalance interval (counted using Equation 43) based on each exogenous variable i.

The total number of possible combinations of the inputs is n^2, where n is the number of exogenous variables (which is 24, which means 24^2 possible combinations). I used optimization to reduce the total number of input variables to get maximized profit.

This optimization was done by the following process. At first, the input of the lagged system imbalance was used for the forecast. Then inputs were gradually added multiplied by its accuracy of the individual forecast (α_i). The total accuracy of the successfully forecasted system imbalance (the model accuracy) was calculated for each input and if the accuracy increased, the input variable was used for the final model. The order of the inputs added into the model was chosen by the accuracy of the individual forecast of the system imbalance (forecast based on the single input).

Inputs used in the model after these optimizations are displayed in Table 37.

Table 37 Inputs used in the model. Source: own calculation.

Intraday market price	Total consumption (real)
Balancing market price (positive only)	Total consumption (forecast)
Balancing market price	Total consumption (adjacent value differences)
German photovoltaic	Total consumption (forecast, adjacent value differences)
German wind (adjacent value differences)	Total consumption (difference between reality and forecast)
Total supply (adjacent value differences)	Export – import (difference between reality and forecast)

The model is validated in terms of profit or loss, which is caused by our speculation based on the forecast of the model.

For the speculation purposes, I have to set the limits for speculation, which have been optimized to reach the maximum profit. Limits were set on the in-sample data, where the value of the limits was changed to achieve the maximal profit made on the speculation. The speculation values for five intervals have been set according Table 38.

Table 38 Speculation values for 5 intervals. Source: own calculation.

Interval number	lower bound [MW]	upper bound [MW]	speculation value [MWh]
-2	-∞	-77	47
-1	-77	-20	10
0	-20	20	0
1	20	104	-2
2	104	∞	-22

For two intervals it is according Table 39.

Table 39 Speculation values for 2 intervals. Source: own calculation.

Interval number	lower bound [MW]	upper bound [MW]	speculation value [MWh]
-2	-∞	0	10
-1	0	∞	-2

The profit and loss from the speculation is calculated as follows:

$$Profit = -Costs * SpecVal + IP * SpecVal \tag{45}$$

The first part of the equation deals with the variable costs connected with the generation of the electricity power (these costs can be also negative, while the speculation is connected with decreasing the output of the power plant – negative costs are the saved fuel and other variable costs). The second part of the equation is the price of the BRP imbalance multiplied by the value of the speculation. Price for the BRP imbalance is determined in the chapter 5.4.

The electricity producer faces the opportunity cost, because if he wants to keep the possibility to speculate in both directions at each hour, he needs to sell the speculative electricity even if the electricity price is lower than the variable costs (negative speculation reserve) and on the other hand, he cannot sell all the electricity (in the case of the electricity price is higher than the variable costs) that can be generated, because of the positive speculation reserve. I present two types of result to capture this in my decision. First, I speculate at each hour and deduct the opportunity costs from the profit. Second, I calculate the profit only for hours when the speculation reserve remains after the day-ahead market, where the position is closed. (It has to be noted here that there is a negative speculation reserve at expensive hours, when the electricity price is higher than the variable costs, and a positive speculation reserve at cheap hours, when the electricity price is lower than the variable costs.) I thus consider the opportunity costs to be caused by keeping the possibility to speculate.

9.3. Benchmark model

I use the ARMA process generally used for this type of forecast in the literature for the comparison of the results of the proposed model.

Autoregressive–moving-average (ARMA) models provide a parsimonious description of a stationary stochastic process in terms of two polynomials, one for the auto-regression and the second for the moving average [37].

Given a time series of data *y(t)*, the ARMA model is a tool for understanding and, perhaps, predicting future values in this series. The model consists of two parts, an autoregressive (AR) part and a moving average (MA) part. The model is usually then referred to as the ARMA(p,q) model where p is the order of the autoregressive part and q is the order of the moving average part. The ARMA process is described by the following difference equation:

$$\left(1 - a_1 E_{\{t-1\}} - \cdots - a_p E_{\{t-p\}}\right) y(t) = c + \left(1 + b_1 E_{\{t-1\}} + \cdots + b_q E_{\{t-q\}}\right) e(t) \qquad (46)$$

Where $y(t)$ is the state output, $e(t)$is white noise input, E is the shift operator, and c is the constant.

I used the Wolfram Mathematica with function *TimeSeriesModelFit*, which leads to the process ARMA(1,1) with c = 3.19134, a = 0.717179 and b = 0.116355 to established the model parameters For the forecast of the in-sample and out-of-sample data we used the function *TimeSeriesForecast*. The results of the forecast are presented in the following chapter.

10. Case Study

Data used for the case study are for the interval from 24 January 2014 to 30 June 2015. From the total of 12 551 hourly data, I used the first 8208 samples (year 2014) for the calibration of the model and the remaining 4343 samples for its validation.

In this chapter, there are used terms of accuracy of interval forecast and the forecast of the system imbalance direction. These terms are defined as follows:

$$IntervalAccuracy = \frac{number\ of\ the\ sucesfully\ forecasted\ SI\ intervals}{number\ of\ the\ forecasted\ data\ samples} \tag{47}$$

$$DirectionAccuracy = \frac{number\ of\ the\ sucesfully\ forecasted\ SI\ directions}{number\ of\ the\ forecasted\ data\ samples} \tag{48}$$

Interval accuracy is calculated from the whole sample of data to show the strength of the model. The direction accuracy is calculated from the data after elimination of the opportunity cost to show the profitability of the model.

10.1. In-sample forecast

From the total of 8208 hours, the interval was forecast successfully for five-interval distributions in 3356 hours, which gives us 41 % accuracy; for two-interval distributions it was correct in 5748 hours, which gives us 70 % accuracy.

The system imbalance direction forecast was 64% for five-interval distribution and 61 % for two-interval distributions.

I find out that keeping a both-sided speculation reserve results in higher opportunity costs than the profit, as can be seen in Table 41. In the case study eliminating the opportunity costs, I reached a profit as can be seen in Table 40. In this case, only 2222 hours were used for the speculation for the five-interval distribution, from which 1428 hours result in an average profit of 388 EUR, and 794 hours result in an average loss of –422 EUR. Besides, only 3256 hours were used for speculation for the two-interval distribution, from which 2006 hours result in an average profit of 193 EUR, and 1260 hours result in an average loss of –234 EUR.

At the benchmark model, the system imbalance direction forecast was 62 % for five-interval distribution and 54 % for two-interval distributions. There were also opportunity costs caused by the need of keeping speculation reserve. By eliminating the opportunity cost, only 1715 hours were used for the speculation, from which 1062 hours result in an average profit of 215 EUR and 653 hours result in average loss of 281 EUR at five-interval distribution. At two-interval distribution, 3684 hours were used for the speculation (after elimination of the opportunity cost) from which 1997 hours result in the average profit of 172 EUR and 1687 hours result in the average loss of 229 EUR. The results are significantly worse than proposed model and prove the value of the proposed model.

Table 40 Accuracy and average profits and losses of the in-sample case study. Source: own calculation.

	Accuracy of interval forecast [%]	**Accuracy of system imbalance forecast [%]**	**Average profit (in profit hours) [EUR/hour]**	**Average loss (in loss hours) [EUR/hour]**
5 intervals - calibration data	41%	64%	388	-422
2 intervals - calibration data	70%	61%	193	-234
5 intervals - calibration data - Benchmark	36%	62%	215	-281
2 intervals - calibration data - Benchmark	65%	54%	172	-229

Decrease of the accuracy from the interval forecast to the system imbalance forecast at two intervals distribution is caused by influencing the system imbalance by our speculation.

What can be a little bit confusing and desire an explanation are the values of the average profit and loss. The higher value of the average loss in compare to the value of the average profit is caused by the system imbalance pricing mechanism in Czech Republic, where the BRP imbalance prices in the opposite direction to the system imbalance (money paid to the BRP) are always lower than the BRP imbalance prices in the same direction to the system imbalance (money paid to the TSO)[15]. This difference makes the profit of the TSO. However these values

[15] These values are expressed in the absolute values and compared relative to the one direction of the system imbalance.

are expressed to one average hour, where the number of successfully forecasted hours (profit) is significantly higher than the number of unsuccessfully forecasted hours (loss), which make the speculation (total sum of the profit and loss) profitable.

Table 41 Profit and opportunity costs of the in-sample case study. Source: own calculation.

	Profit [EUR]	**Opportunity costs [EUR]**	**Profit eliminating opportunity costs [EUR]**
5 intervals - calibration data	888 518	2 724 492	218 078
2 intervals - calibration data	447 751	476 734	93 017
5 intervals - calibration data - Benchmark	262 839	2 724 492	44 901
2 intervals - calibration data - Benchmark	170 405	476 734	-32 005

Better results were obtained from the model with five-interval distribution, which confirmed the hypothesis that a model with more intervals can lower the risk and make higher profits (lower losses).

The Benchmark model shows significantly lower profit gain from the speculation in comparison to the proposed model, which again proves the value of the proposed model. At the two-interval distribution model eliminating opportunity cost even shows loss. All the results are displayed in the Table 41Table 41.

10.2. Out-of-sample forecast

The rest of the data set (year 2015) has been used for the validation of the model in the out-of-sample forecast. The results obtained are in accordance with the results obtained in the in-sample forecast. From the total of 4343 hours, the interval was forecast successfully in 1755 hours for five-interval distributions, which gives us 40 % accuracy and in 3050 hours for two-interval distributions, which gives us 70 % accuracy.

The system imbalance direction forecast was 61% for five-interval distribution and 60 % for two-interval distributions.

There is only a small decrease in the average profit (counted per day in the interval of the forecast), which was expected due to the fact that I did not recalibrate the model on the validation data. In the case study eliminating the opportunity costs, I again reached a profit as can be seen in Table 43. Here, only 1332 hours were used for the speculation for the five-interval distribution, from which 825 hours result in an average profit of 504 EUR, and 507 hours result in an average loss of –639 EUR; and only 1682 hours were used for speculation for the two-interval distribution, from which 1022 hours result in an average profit of 224 EUR and 660 hours result in an average loss of –270 EUR.

At the benchmark model, the system imbalance direction forecast was 66 % for five-interval distribution and 58 % for two-interval distributions. There was also opportunity cost caused by the need of keeping speculation reserve. By eliminating the opportunity cost, only 870 hours were used for the speculation, from which 575 hours result in an average profit of 243 EUR and 295 hours result in average loss of 361 EUR at five-interval distribution. At two-interval distribution, 1851 hours were used for the speculation (after elimination of the opportunity cost) from which 1072 hours result in the average profit of 208 EUR and 779 hours result in the average loss of 260 EUR. The results are significantly worse than proposed model and prove the value of the proposed model.

Table 42 Accuracy and average profit and loss of the out-of-sample case study. Source: own calculation.

	Accuracy of interval forecast [%]	**Accuracy of system imbalance forecast [%]**	**Average profit (in profit hours) [EUR/hour]**	**Average loss (in loss hours) [EUR/hour]**
5 intervals - calibration data	40%	61%	504	-639
2 intervals - calibration data	70%	60%	224	-270
5 intervals - calibration data – Benchmark	37%	66%	243	-361
2 intervals - calibration data – Benchmark	67%	58%	208	-260

The decrease in the accuracy from the interval forecast to the system imbalance forecast with the two-interval distribution is caused by our speculation influencing the system imbalance. The opportunity costs were again significantly higher than the profit reached, so I made the forecast again only in hours where the speculation reserve remains after the day-ahead market; see Table 42.

Table 43 Profit and opportunity costs of the out-of-sample case study. Source: own calculation.

	Profit [EUR]	Opportunity costs [EUR]	Profit eliminating opportunity costs [EUR]
5 intervals - validation data	463 820	1 262 743	91 996
2 intervals - validation data	192 855	199 674	50 576
5 intervals - calibration data - Benchmark	144 482	1 262 743	32 990
2 intervals - calibration data - Benchmark	111 859	199 674	20 485

From both in-sample and out-of-sample forecast results, we can see that the average loss is significantly higher than the average profit, which confirms the need for reducing the risk and maximization of the number of hours in which the forecast is successful (accurate). I reached a profit because of a significantly higher number of hours which were forecast correctly than the number of hours in which the forecast failed.

Validation confirmed a properly set boundary of the intervals, which brings an even higher average profit and comparable accuracy of the forecast model.

The Benchmark model shows significantly lower profit gain from the speculation in comparison to the proposed model, which again proves the value of the proposed model. All the results are displayed in the Table 43.

11. Hypothesis evaluation

In this chapter, I evaluate the hypothesis declared in the chapter 3. As the hypothesis deals mostly with usability and applicability of the input exogenous variables, the most important chapters of the whole work are chapters 8. – 10.

Hypothesis of the work were:

1. System imbalance value can be forecasted with sufficient accuracy to gain the profit speculating on the opposite position of the BRP imbalance

This hypothesis has been **approved**. It was shown, that it is able to forecast the system imbalance in order to gain profit despite the fact of high volatility and sudden changes of this data set.

For the forecast of the system imbalance were used model as the weighted sum of the filtrated and interval distributed input exogenous variables. The evaluation of the model was model was made both on the in-sample and out-of-sample data.

For the in-sample forecast were used data from 24 January 2014 to 30 June 2015. From the total of 12 551 hourly data, I used the first 8208 samples (year 2014) for the calibration of the model and the remaining 4 343 samples for its validation. From Table 44 can be seen that profit from in-sample forecast was for 5 interval distributed data 218 078 EUR after elimination of the opportunity costs, which were 2 724 492 EUR against the profit of 888 518 EUR. For 2 interval distributed data the result from the speculation were 93 017 EUR profit after elimination of the 476 734 EUR of the opportunity costs against profit of 447 751 EUR.

Elimination of the opportunity cost (by limited speculations in the hours, where the opportunity costs occur) brought very high profit in both 5 and 2 interval distributed data.

Table 44 Profit and loss - in-sample forecast. Source: own calculation.

	Profit [EUR]	Opportunity costs [EUR]	Profit eliminating opportunity costs [EUR]
5 intervals - calibration data	888 518	2 724 492	218 078
2 intervals - calibration data	447 751	476 734	93 017

For the out-of-sample forecast were used data from 1 January 2015 to 30 June 2015. The profit decreased slightly against in-sample forecast, but remains high enough for approving the hypothesis of "in-money speculation". From Table 45 can be seen that profit from in-sample forecast was for 5 interval distributed data 91 996 EUR after elimination of the opportunity costs, which were 1 262 743 EUR against the profit of 463 820 EUR. For 2 interval distributed data the result from the speculation were 50 576 EUR profit after elimination of the 199 674 EUR of the opportunity costs against profit of 192 855 EUR.

Elimination of the opportunity cost brought again (as in the in-sample forecast) very high profit in both 5 and 2 interval distributed data.

Table 45 Profit and loss - out-of-sample forecast. Source: own calculation.

	Profit [EUR]	**Opportunity costs [EUR]**	**Profit eliminating opportunity costs [EUR]**
5 intervals - validation data	463 820	1 262 743	91 996
2 intervals - validation data	192 855	199 674	50 576

1.1 System imbalance value can be forecasted with sufficient accuracy to gain the profit speculating on the opposite poInputs described in this dissertation are relevant for the system imbalance forecast and their usage in the forecasting methodology improve the accuracy of the final system imbalance forecast. of the BRP imbalance

This hypothesis has been **partially approved**. In the analysis part of the work, I defined 24 exogenous variables seems to be usable for the forecast of the system imbalance. These variables were defined based on the settlement of the imbalance price in Czech republic and other markets, factors influencing the supply and demand, which difference create the system imbalance and on the personal experience of the system imbalance development.

From the Annex A and B can be seen that individual system imbalance forecasts for the five-interval distribution based on individual exogenous variables were between 25 and 37% accuracy of successfully forecast intervals, and between 11 and 59% accuracy of successfully forecast system imbalance (except the balance market, which has non-zero values only in a few hours). For the two-interval distribution the accuracy was between 55 and 66%. After optimizing the interval limits for data distribution, I set the model as the sum of the vector multiplications of the system imbalance forecast based on each exogenous variable and the percentage accuracy of the successful forecast of the exogenous variable. I found out that not every exogenous variable can be used for the final model forecast as its forecast based on the exogenous variable decreases the accuracy of the final forecast.

After optimization, I used following exogenous variables: Intraday market price, Total consumption (real), Balancing market price (positive only), Total consumption (forecast), Balancing market price, Total consumption (adjacent value differences), German photovoltaic, Total consumption (forecast, adjacent value differences), German wind (adjacent value differences), Total consumption (difference between reality and forecast), Total supply (adjacent value differences), Export – import (difference between reality and forecast).

2. Interval forecast can lead to better prediction than two-sided interval. Hypothesis is based on the assumption that the two-sided forecast cannot reduce the risk of the changing the direction of the system imbalance by the BRP's imbalance speculation. Interval forecast can also increase the profit by changing speculation level (BRP's imbalance value) among the intervals.

This hypothesis has been **approved**. I calculated the accuracy of the system imbalance forecast in both 2 interval distributed data (two-sided forecast) and 5 interval distributed data in both in-sample and out-of-sample data. The result is that the use of more intervals with defined speculation level decreases the risk of high payment for the BRP imbalance in the same direction as the system imbalance. Next I defined the zero intervals, with very high risk and eliminated this interval from the forecast, which again increased the accuracy of the forecast.

From Table 46 can be seen that on the in-sample data the accuracy of the successfully forecasted interval by 5 intervals distributed data was 41 % and by 2 intervals distributed data was 70 %. Accuracy of the system imbalance forecast was 64 % for 5 intervals distributed data and 61 % for the 2 intervals distributed data.

Table 46 Accuracy of the forecast - in sample forecast. Source: own calculation.

	Accuracy of interval forecast [%]	**Accuracy of system imbalance forecast [%]**	**Average profit (in profit hours) [EUR/hour]**	**Average loss (in loss hours) [EUR/hour]**
5 intervals - calibration data	41%	64%	388	-422
2 intervals - calibration data	70%	61%	193	-234

From Table 47Table 47 can be seen that on the out-of-sample data the accuracy of the successfully forecasted interval by 5 intervals distributed data was 40 % and by 2 intervals distributed data was 70 %. Accuracy of the system imbalance forecast was 61 % for 5 intervals distributed data and 60 % for the 2 intervals distributed data.

Table 47 Accuracy of the forecast - out-of sample forecast. Source: own calculation.

	Accuracy of interval forecast [%]	Accuracy of system imbalance forecast [%]	Average profit (in profit hours) [EUR/hour]	Average loss (in loss hours) [EUR/hour]
5 intervals - calibration data	40%	61%	504	-639
2 intervals - calibration data	70%	60%	224	-270

3. The intra-hour trend of the system imbalance is a relevant input for the hourly system imbalance forecast. There is a relation between the intra-hour trend of the system imbalance and hourly system imbalance.

This hypothesis has been **disapproved**. In the chapter 7 was proved that there is not significant relation between the intra-hour trend of the system imbalance and hourly system imbalance. However, the forecast of this data was showed to be important for the TSO and intra-hour imbalance speculation of the BRPs.

4. Logical relation between German and Czech power markets exists. Quickly increasing share of RES power generation affects the Czech system imbalance.

This hypothesis has been **approved**. I used the German PV and wind data. From these data I used really measured values, calculated the difference between planned and actually measured data and calculated the difference between neighbour data (hourly change in the production) for the wind production. These values showed the ability of the individual forecast of the system imbalance between 24 – 33 % at the 5 interval distributed data and 36 – 53 % at the 2 interval distributed data. These results are very similar to the accuracies forecast of the Czech PV and wind generation. From the total of 15 input exogenous variables used for the final model of the forecast of the system imbalance, two inputs were from German data: German photovoltaic (actual measured data) and German wind (adjacent value differences), which shows the importance of these data for the final forecast.

12. Conclusion

The interconnected European electricity markets bring new possibilities for market participants. At the same time, however, there is a reciprocal influence of markets, which should be taken in account while analysing the markets. My new methodology of predicting system imbalance proved (on the case of the Czech Republic and Germany) that there are linkages between electricity markets, which influence the system imbalance. This methodology is internationally portable and can be used across interconnected markets.

In the last 9 years, the total sum of the BRP imbalances in the opposite direction to the system imbalance increased, even the BRP imbalance in the same direction to the system imbalance decreased, which prove the importance of the BRP imbalances in the opposite direction to the system imbalance.

The seasonality of the system imbalance was not found on the sufficient level for using pure auto regression model. Therefore there is the need of usage of the more exogenous variables.

I have set the hypothesis of the usage of the intra-hour system imbalance trend for the forecast of the hourly average system imbalance value. The forecast of the intra-hour trend of the system imbalance showed promising results. The model is based on the changes of the demand and the supply of RES (Renewable energy sources) power generation between previous and forecasted hour returned better results than the model based on the changes of the demand and the supply of RES power generation between forecasted and following hour. The best results were achieved by the combination of both of these inputs and making a forecast only in the hour, where the partial forecast of both models are identical. Therefore the forecast is made only in 2 534 hours (59 % of the whole data set), but the accuracy arises from 67.5 % (67 %) to 79.4 % of the successfully forecasted intra-hour system imbalances trends. The filtration of the beginning and the last 5 minutes of each hour did not bring the expected improvement and were evaluated as insignificant.

The relation between system imbalance hourly average value and the intra-hour system imbalance trend was not proven and so the intra-hour system imbalance trend cannot be used for the hourly average system imbalance forecast. On the other hand, the usefulness of this value was demonstrated for the TSO's balancing approach and for intra-hour BRP imbalance optimization as this optimization brings the additional information for the BRP (current development of the system imbalance in the hour).

I have collected data from several exogenous variables, which provided a strong data set for the forecast of the system imbalance. As I aim to speculate on the opposite direction of the BRP imbalance to the system imbalance, I do not need to know the accurate system imbalance, but I need to know the interval, in which the system imbalance is, to minimize the risk of loss, when our speculation fails. I suggested using two types of interval data distribution: two and five intervals, from which the five-interval data distribution provided better results as five intervals offer higher risk reduction. Individual system imbalance forecasts for the five-interval distribution based on individual exogenous variables were between 25 and 37 % accuracy of successfully forecast intervals, and between 11 and 59 % accuracy of successfully forecast system imbalance (except of the balance market, which has non-zero values only during a few hours). For the two-interval distribution the accuracy was between 55 and 66 %. After optimizing the interval limits for data distribution, I set the model as the sum of the vector multiplications of the system imbalance forecast based on each exogenous variable and the percentage accuracy of the successful forecast of the exogenous variable. I found out that not every exogenous variable can be used for the final model forecast as its forecast based on the exogenous variable decreases the accuracy of the final forecast. Among other facts, the study result is that not only Czech market variables but also German RES power generation affects the Czech system imbalance. After optimization, I used following exogenous variables: Intraday market price, Total consumption (real), Balancing market price (positive only), Total consumption (forecast), Balancing market price, Total consumption (adjacent value differences), German photovoltaic, Total consumption (forecast, adjacent value differences), German wind (adjacent value differences), Total consumption (difference between reality and forecast), Total supply (adjacent value differences), Export – import (difference between reality and forecast).

The accuracy of the model was about 40 % of successful forecast intervals and 64 % of successful forecast system imbalances for the five-interval distribution and 70 % of successful forecast intervals and 60 % of successful forecast system imbalances for the two-interval distribution. I can see from the results that the model significantly increased the accuracy of both the successfully forecast intervals and system imbalances compared to the forecast based on individual exogenous variables.

For the speculation at each hour, I found out significant opportunity costs (1262 thousand EUR for five intervals and 200 thousand EUR for five intervals) for the electricity producer, which exceeded the realized profits (464 and 193 thousand EUR, respectively), so I suggested speculating only at hours with the remaining speculation reserve from the day-ahead market (eliminating opportunity costs). This approach resulted in a profit of 92 thousand EUR for the five-interval distribution and 51 thousand EUR for the two-interval distribution in the out-of-sample forecast. Higher profit was obtained in both the in-sample forecast and the out-of-sample forecast using the model with the five-interval distribution.

I have also used, in the literature widely used ARMA model, as a benchmark model to the proposed model. In most cases (except 2 interval distributed model eliminating opportunity costs forecasting the in-sample data) the model resulted in the profit, but significantly lower than proposed model, which proved the better accuracy system imbalance forecast of the proposed model.

The proposed methodology of interval distribution is applicable to solving similar tasks where the exact value of the predicted dependent variable, such as a cross-border capacity forecast, etc., is not important.

13. Suggestions for future work

The model presented in this thesis reflects the energy market and the energy mix in the time of its creation. For the successful application of the model, the inputs have to be reviewed according to the change of the market situation. Here are few possibilities of the future changes, which could affect the forecast of the system imbalance:

- *Change of the PTU (programme time unit)* – This is the period of the settlement of the system imbalance. PTU is in Czech Republic 60 minutes, which is quite rare as almost all other European states have only 15 minutes PTU. The change from 60 minutes to 15 minutes would change the forecast very dramatically, and the usage of the exogenous variables would be different.
- *Increasing share of the RES in power generation* – The increasing share of the RES in power generation without sufficient energy storage could lead to the increasing volatility of the system imbalance with the increasing amount of the auxiliary services. This should have to be solved by the increasing weight of these inputs in the forecast model. [43, 44]
- *Stability of the energy grid* – Problem with the stability of the energy grid can lead to the capacity payment, which would lead to completely different market structure. In this case, the intraday and day-ahead price for the electricity could not be used and have to be replaced by another exogenous variables. [47]

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Annex A: Calibration data

Table A.1: calibration data

IMP = intraday market price, SDAMP = spot day-ahead market price, BMP = balancing market price, Diff = difference between reality and forecast, AVD = adjacent value differences

	IMP	SDAP	BMP+	BMP-	BMP	photo voltaic CZ real.	photo voltaic CZ diff	photo voltaic DE real.	photo voltaic DE diff	wind DE real.	wind DE change	wind DE diff	Total supply real.	Total supply change	Total consumption – real	Total consumption. Change	export - import real	export - import diff	Total supply - plan	Total supply - plan change	Total supply - plan minus real	Total consumption - plan	Total consumption - plan change	Total consumption - plan minus real
Quantity	4305	4343	523	1076	4343	2520	2534	2633	2637	4343	4343	4342	4343	4343	4343	4343	4343	4343	4343	4343	4343	4343	4343	4343
interval boundary-2/-1	54	71.5	16	50	16	-12	173	-5	4500	750	-2000	2105	5968	-700	9001	756	-3123	40	7456	-256	897	9027	150	-190
interval boundary -1/0	37.4	44.7	6	41	1	78	110	1280	2000	2123	-738	1201	7501	-178	7059	101	-2463	5	8976	0	0	8126	-96	-129
interval boundary 0/1	32.8	35.4	3	33	-1	298	20	2717	0	3212	0	0	9123	-7	6230	-99	-1897	-26	10112	196	-560	7453	-219	-44
interval boundary 1/2	4.3	0.9	-3	-42	-44	1332	-248	13475	-2000	14456	983	-4090	11497	732	5112	-334	-1265	-48	10873	456	-1000	6243	-421	101
correctly stated intervals – 5 intervals	1566	1397	206	552	1494	627	922	655	715	1411	1150	1336	1234	1215	879	1023	1021	730	883	827	933	1023	390	569
	36.38 %	**32.17 %**	**39.39 %**	**51.30 %**	**34.40 %**	**24.88 %**	**36.39 %**	**24.88 %**	**27.11 %**	**32.49 %**	**26.48 %**	**30.77 %**	**28.41 %**	**27.98 %**	**20.24 %**	**23.56 %**	**23.51 %**	**16.81 %**	**20.33 %**	**19.04 %**	**21.48 %**	**23.56 %**	**8.98%**	**13.10 %**
Forecast -2nd interval	295	3	0	0	225	0	260	0	95	41	220	283	1	57	1063	125	243	715	404	606	16	880	6057	0
Forecast -1st interval	993	503	0	0	292	677	272	703	420	516	698	277	237	941	2301	1012	901	1443	1207	1793	975	926	3384	0

Forecast 0th interval	525	883	0	0	2748	531	687	260	1488	549	1309	976	1293	1337	775	1595	991	1486	1169	1145	2272	922	1724	0
Forecast 1st interval	2421	2886	0	866	874	1174	1998	1176	1086	2494	1428	2343	2099	1903	204	1159	1141	397	576	503	745	1201	926	0
Forecast 2nd interval	71	69	0	210	201	138	181	494	96	743	688	464	713	105	0	452	1067	302	987	296	335	414	460	4343
Correctly stated -2nd interval	114	0	109	0	109	0	94	0	23	2	13	22	0	3	164	9	14	5	9	38	0	144	390	0
Correctly stated -1st interval	236	113	61	0	87	127	59	118	67	96	129	48	32	166	401	174	165	182	236	330	139	148	0	0
Correctly stated 0th interval	167	168	35	0	752	100	98	51	238	161	356	282	324	314	228	366	257	473	281	248	509	231	0	0
Correctly stated 1st interval	1008	1086	1	411	412	364	604	373	368	952	539	888	802	724	86	436	438	69	234	191	277	469	0	0
Correctly stated 2nd interval	41	30	0	141	134	36	77	113	19	200	113	96	76	8	0	38	147	1	123	20	8	31	0	569
correctly stated imbalances – 5 intervals	2517	2207	345	914	1308	1139	1483	1288	878	2279	1601	1979	1787	1650	1459	1449	1796	531	1540	1460	909	1837	1627	2716
	58.47 %	**50.82 %**	**65.97 %**	**84.94 %**	**30.12 %**	**45.20 %**	**58.52 %**	**48.92 %**	**33.30 %**	**52.48 %**	**36.86 %**	**45.58 %**	**41.15 %**	**37.99 %**	**33.59 %**	**33.36 %**	**41.35 %**	**12.23 %**	**35.46 %**	**33.62 %**	**20.93 %**	**42.30 %**	**37.46 %**	**62.54 %**
interval boundary - 1/1	45.22	46.5	1	5	2	-1	92	-5	1500	619	-4970	6630	0	-1464	-5	531	-3919	347	0	-945	2630	8501	751	-101
correctly stated intervals – 2 intervals	2860	2721	397	914	3339	1562	1739	1627	1607	2717	2712	2715	2716	2716	2716	2673	2714	2716	2716	2713	2716	2488	1627	2716
	66.43 %	**62.65 %**	**75.91 %**	**84.94 %**	**76.88 %**	**61.98 %**	**68.63 %**	**61.79 %**	**60.94 %**	**62.56 %**	**62.45 %**	**62.53 %**	**62.54 %**	**62.54 %**	**62.54 %**	**61.55 %**	**62.49 %**	**62.54 %**	**62.54 %**	**62.47 %**	**62.54 %**	**57.29 %**	**37.46 %**	**62.54 %**
Forecast -1st interval	669	390	224	0	539	0	616	0	697	13	4	5	0	0	0	195	2	0	0	15	0	1258	4343	0
Forecast 1st	3626	3954	3	1076	4260	2520	2782	2633	2487	4330	4339	4338	4343	4343	4343	4148	4341	4343	4343	4328	4343	3085	0	4343

interval																								
Correctly stated -1st interval	418	197	395	0	410	0	314	0	273	7	0	2	0	0	0	76	0	0	0	6	0	515	1627	0
Correctly stated 1st interval	2442	2524	2	914	2929	1562	1425	1627	1334	2710	2712	2713	2716	2716	2716	2597	2714	2716	2716	2707	2716	4973	0	2716

Annex B: Testing data

Table B.1: testing data

	IMP	SDAP	BMP+	BMP-	BMP	photovoltaic CZ real.	photovoltaic CZ diff	photovoltaic DE real.	photovoltaic DE diff	wind DE real.	wind DE change	wind DE diff	Total supply real.	Total supply change	Total consumption – real	Total consumption. Change	export-import real	export-import diff	Total supply - plan	Total supply - plan change	Total supply - plan minus real	Total consumption - plan	Total consumption - plan change	Total consumption - plan minus real
Quantity	7752	8208	1157	2013	8208	4854	4872	4780	4789	8208	8208	7296	8208	8208	8208	8208	8208	8208	8208	8208	8208	8208	8208	8208
interval boundary-2/-1	54	71.5	16	50	16	-12	173	-5	4500	750	-2000	2105	5968	-700	9001	756	-3123	40	7456	-256	897	9027	150	-190
interval boundary -1/0	37.4	44.7	6	41	1	78	110	1280	2000	2123	-738	1201	7501	-178	7059	101	-2463	5	8976	0	0	8126	-96	-129
interval boundary 0/1	32.8	35.4	3	33	-1	298	20	2717	0	3212	0	0	9123	-7	6230	-99	-1897	-26	10112	196	-560	7453	-219	-44
interval boundary 1/2	4.3	0.9	-3	-42	-44	1332	-248	13475	-2000	14456	983	-4090	11497	732	5112	-334	-1265	-48	10873	456	-1000	6243	-421	101
correctly stated intervals – 5 intervals	**2849**	**2775**	**450**	**1088**	**3065**	**1317**	**1520**	**1210**	**1250**	**2537**	**2255**	**2316**	**2364**	**2266**	**1992**	**2186**	**1962**	**1538**	**1659**	**1503**	**1737**	**2107**	**1715**	**2740**
	36.75 %	**33.81 %**	**38.89 %**	**54.05 %**	**37.34 %**	**27.13 %**	**31.20 %**	**25.31 %**	**26.10 %**	**30.91 %**	**27.47 %**	**31.74 %**	**28.80 %**	**27.61 %**	**24.27 %**	**26.63 %**	**23.90 %**	**18.74 %**	**20.21 %**	**18.31 %**	**21.16 %**	**25.67 %**	**20.89 %**	**33.38 %**
Forecast - 2nd interval	918	19	493	0	496	0	484	0	158	217	182	298	36	43	852	224	569	805	870	973	507	817		906
Forecast -1st interval	2138	1412	423	0	661	1455	385	1280	545	1913	1071	356	663	1612	4115	1922	1525	2636	2741	3558	2694	1543		601
Forecast 0th interval	819	1960	221	0	5046	1046	907	515	1354	1362	2923	1775	2743	2756	1913	3028	1844	3296	2206	2207	2825	1732		1560
Forecast 1st interval	3726	4749	20	1796	1802	2204	1777	2043	1681	4072	3149	4436	4267	3704	1263	2282	2279	831	1312	956	1074	2723		3414
Forecast 2nd	151	68	0	217	206	149	455	942	504	644	883	431	499	93	65	752	1991	640	1079	514	1108	1393		1727

interval																								
Correctly stated -2nd interval	282	3	235	0	235	0	207	0	47	40	17	20	5	2	151	25	74	6	59	38	33	130	202	248
Correctly stated -1st interval	521	293	140	0	213	325	104	272	131	352	183	67	90	249	744	400	269	208	459	586	451	296	578	157
Correctly stated 0th interval	267	479	67	0	1530	256	271	127	350	396	783	498	711	744	536	775	529	1159	567	544	770	424	494	479
Correctly stated 1st interval	1695	1952	8	976	980	706	821	617	663	1598	1154	1678	1522	1263	549	932	882	158	429	298	398	1120	405	1428
Correctly stated 2nd interval	84	48	0	112	107	30	117	194	59	151	118	53	36	8	12	54	208	7	145	37	85	137	36	428
correctly stated imbalances – 5 intervals	**4624**	**3951**	**741**	**1741**	**2635**	**2131**	**2392**	**2225**	**1712**	**3880**	**2932**	**3203**	**2979**	**2744**	**3171**	**3056**	**3428**	**920**	**2651**	**2508**	**2423**	**3842**	**3072**	**4606**
	59.65 %	**48.14 %**	**64.04 %**	**86.49 %**	**32.10 %**	**43.90 %**	**49.10 %**	**46.55 %**	**35.75 %**	**47.27 %**	**35.72 %**	**43.90 %**	**36.29 %**	**33.43 %**	**38.63 %**	**37.23 %**	**41.76 %**	**11.21 %**	**32.30 %**	**30.56 %**	**29.52 %**	**46.81 %**	**37.43 %**	**56.12 %**
interval boundary -1/1	45.22	46.5	1	5	2	-1	92	-5	1500	619	-4970	6630	0	-1464	-5	531	-3919	347	0	-945	2630	8501	751	-101
correctly stated intervals – 2 intervals	**5115**	**5012**	**899**	**1741**	**5255**	**2670**	**3019**	**2629**	**2618**	**4997**	**4975**	**4463**	**4975**	**4975**	**4975**	**5005**	**4989**	**4975**	**4975**	**4968**	**4975**	**4894**	**4995**	**5440**
	65.98 %	**61.06 %**	**77.70 %**	**86.49 %**	**64.02 %**	**55.01 %**	**61.97 %**	**55.00 %**	**54.67 %**	**60.88 %**	**60.61 %**	**61.17 %**	**60.61 %**	**60.61 %**	**60.61 %**	**60.98 %**	**60.78 %**	**60.61 %**	**60.61 %**	**60.53 %**	**60.61 %**	**59.62 %**	**60.86 %**	**66.28 %**
Forecast -1st interval	1834	1168	1448	0	1122	0	1015	0	924	110	0	3	0	0	0	314	32	2	0	27	0	1505	222	1933
Forecast 1st interval	5918	7039	3	2013	6630	4854	2993	4780	3318	8098	8208	7293	8208	8208	8208	7894	8176	8206	8208	8181	8208	6703	7986	6275
Correctly stated -1st interval	1136	603	897	0	873	0	749	0	517	66	0	2	0	0	0	172	23	1	0	10	0	712	121	1199
Correctly stated 1st	3979	4409	2	1741	4382	2670	2270	2629	2101	4931	4975	4461	4975	4975	4975	4833	4966	4974	4975	4958	4975	4182	4874	4241

interval

Annex C: Wolfram Mathematica – Optimization code

```
BoundariesSI = {-80, -20, 20, 115};
IntervalNumber[number_] :=
 Piecewise[{{1, number < BoundariesSI[[1]]}, {2, number < BoundariesSI[[2]]},
   {3, number < BoundariesSI[[3]]}, {4, number < BoundariesSI[[4]]}, {5, number >= BoundariesSI[[4]]}}]
Clear[input]
input = Import[NotebookDirectory[] <> "WIND_DEU_DIFF_OPP_13.xlsx"];
SI = Table[input[[1, i, 1]], {i, Length[input[[1]]]}];
inputData = Table[input[[1, i, 2]], {i, Length[input[[1]]]}];
x1 = Map[IntervalNumber[#] &, SI];
IntervalData[number_, v1_, v2_, v3_, v4_] :=
 Piecewise[{{1, number > v1}, {2, number > v2}, {3, number > v3}, {4, number > v4}, {5, number <= v4}}]
x2 = Map[IntervalData[#, v1, v2, v3, v4] &, inputData];
funcMax = Sum[If[x1[[i]] == x2[[i]], 1, 0], {i, Length[inputData]}];

NMaximize[{funcMax, v1 > v2 && v2 > v3 && v3 > v4 }, {v1, v2, v3, v4},
 Method → {"SimulatedAnnealing", "PerturbationScale" → 3000, "LevelIterations" → 400},
 WorkingPrecision → 6]

NMaximize[{funcMax, v1 > v2 && v2 > v3 && v3 > v4 }, {v1, v2, v3, v4},
 Method → {"DifferentialEvolution", "ScalingFactor" → 1}, WorkingPrecision → 6]

body = Flatten[Table[{n1, n2, n3, n4}, {n1, 6000, 7000, 500}, {n2, 4500, 5500, 500},
    {n3, 4000, 4500, 500}, {n4, -5000, -3000, 1000}], 3];

NMaximize[{funkceMax, v1 > v2 && v2 > v3 && v3 > v4 }, {v1, v2, v3, v4},
 Method → {"SimulatedAnnealing", "PerturbationScale" → 100, "LevelIterations" → 300,
   "InitialPoints" → body}, WorkingPrecision → 6]

NMaximize[{funkceMax, v1 > v2 && v2 > v3 && v3 > v4 }, {v1, v2, v3, v4},
 Method → {"DifferentialEvolution", "ScalingFactor" → 0.5, "InitialPoints" → body},
 WorkingPrecision → 6]
```