Impact of solar production on Czech electricity grid system imbalance

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Abstract. We consider the electricity grid imbalance settlement mechanism in the Czech Republic. We focus on the influence of photovoltaic electricity on the behavior of the system imbalance in this mechanism. Out of the family of GARCH models, we use TARCH model, which allows different behavior if the residual are negative, to model the asymmetric effect of positive or negative electricity system imbalance. Our results show that the introduction of photovoltaics has substantial effect on the Czech electricity system imbalance, leading to positive system imbalance. The influence of photovoltaics on the volatility of the Czech electricity system imbalance is statistically significant, but it is not substantial in economic terms.

Key words: solar; photovoltaics; electricity; system imbalance

JEL classification: Q41, Q42, Q47

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1. Introduction

The key aspect of the smooth integration of renewable electricity resources into existing electricity grid is the functioning imbalance settlement mechanism, which allocates appropriate pricing for excessive production or excessive consumption. As far as our knowledge is concerned, there does not exist any article dealing with electricity system balancing market in the Czech Republic, which is a subject of our interest. We focus on the Czech electricity system imbalance and how it is affected by the solar production. We use GARCH models to assess co-movements of the system imbalance and photovoltaic output. We aim to determine, whether the solar production had the effect on the size and the volatility of the system imbalance.

While the Czech electricity market is not globally important by its size, it is important from the European grid management point of view. In particular the Czech electric grid is important for balancing electricity flows between eastern and western Germany and the connecting networks. Also the Czech electricity market is interesting due to its well-diversified production mix including both renewable sources, primarily photovoltaics, and the nuclear power. As opposed to neighboring Germany, the Czech Republic is committed to keeping its nuclear power station potential and it is engaged in the policy discussion about possible renewal and expansion of Czech nuclear power generation simultaneously with supporting renewable energy.

The theoretical and institutional aspect of renewable resources grid integration are discussed by Vandezande, Meeus, Belmans, Saguan, & Glachant (2010). They propose that due to the fact that renewable source are variable and hardly predictable, the grid integration of renewables requires fully-functioning balancing market that satisfies three conditions.

The first condition is that the imbalance settlements should not contain penalties or power exchange prices. The second rule is that the capacity payments should be allocated to imbalanced balance responsible parties through the additive component in the imbalance price. The last condition is that a cap should be imposed on the amount of reserves. The authors also stress that successful implantation of the balancing mechanism needs, due to its complexity, cross-border cooperation.

Musgens, Ockenfels, & Peek (2014) discuss the technical aspects of the balancing market. Currently the market in Germany function as pay-as-bid mechanism. However, Musgens et al. (2014) suggest that the design should switch to the uniform pricing. The role of scoring is emphasized. Their solution is a merger of two concepts. The settlement based on uniform pricing assures the efficient bids in the balancing market. The second component, the scoring on the grounds of capacity ensures adequate production schedule. Study claims that if the agents are rational the proposed mechanism will maintain efficiency in both balancing and wholesale electricity markets.

2. Czech electricity market and system imbalance

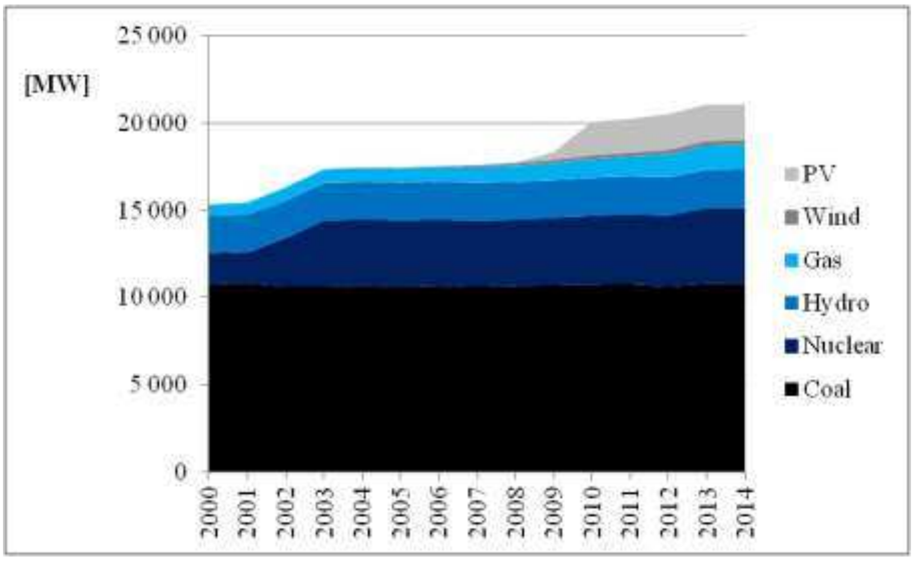
2.1. Czech electricity production

The Czech Republic relies mainly on coal and nuclear energy as far as the production of electricity is concerned. Other sources are hydro power plants including pumped-storage ones. These sources are accompanied with gas stations and renewables. The Czech grid is connected with all its four neighbors. The Czech, Slovak and Hungarian electricity markets have been coupled since 2012. The Polish and Romanian markets should be added in the future.

Since 2000 two significant events influenced the Czech energy mix. The first one was the launch of nuclear power plant Temelín in the beginning of 2000's. The second event is the emergence of the renewable energy.

Notably the use of solar energy exponentially emerged literally from zero to 10 % of total installed capacity. The **Chyba! Nenalezen zdroj odkazů.** depicts the development of installed capacity since 2000 with visible increment of newly installed photovoltaic power plants.

Figure 2.1: Development of installed capacity



2.2. System imbalance and regulatory market

In this section we will introduce the concept of system imbalance and the way how it is treated. The system imbalance is the mismatch between the real production and consumption of electricity. If this happens the grid operator (CEPS) has to use additional back-up resource or decrease the production. CEPS than measures the overall system imbalance and individual imbalances as well.

Subjects of settlement are rewarded or penalized according to the type of their own imbalance. If a subject of settlement helps to bring the grid to stability, it is rewarded for it. However, if its imbalance has the same direction as the overall one, it has to pay a penalty.

OTE (Czech electricity and gas market operator) defines market participants, who are responsible for their own imbalance as subjects of settlement. Not every electricity producer or consumer is a clearance subject. Still, every production or consumption has to be assigned to a clearance subject. As of June 2015 OTE registers around 100 subjects. These are mostly energy trading companies, big producers or big customers.

Households are not subjects of settlement but their responsibility is taken over by their supplier. The supplier is motivated by the system of penalties to minimize its own imbalance.

The imbalance of a subject of settlement is the difference between the electricity supplied to the grid or purchased energy and the consumption. The method used by Czech OTE operator for calculating individual imbalance is shown in the Figure 2.2. Imbalances are calculated for every hour. The first trading hour lasts from 0:00 to 1:00, the second one from 1:00 to 2:00 etc.

Figure 2.2: Clearance subject's imbalance

+	**Production supplied to the grid**
–	**Consumption from the grid**
+	**Short-term markets balance**
+	**Balance from bilateral contracts registered by OTE**

+	Export/Import balance	
	Clearance subject's imbalance	

Source: OTE

System imbalance in each hour is equal to the sum of individual imbalances. It is shown in the Equation 2.1. The system imbalance is covered by CEPS by regulatory energy. CEPS can acquire regulatory energy from three sources. It can active back-up sources, acquire energy from regulatory market or obtain the energy from abroad.

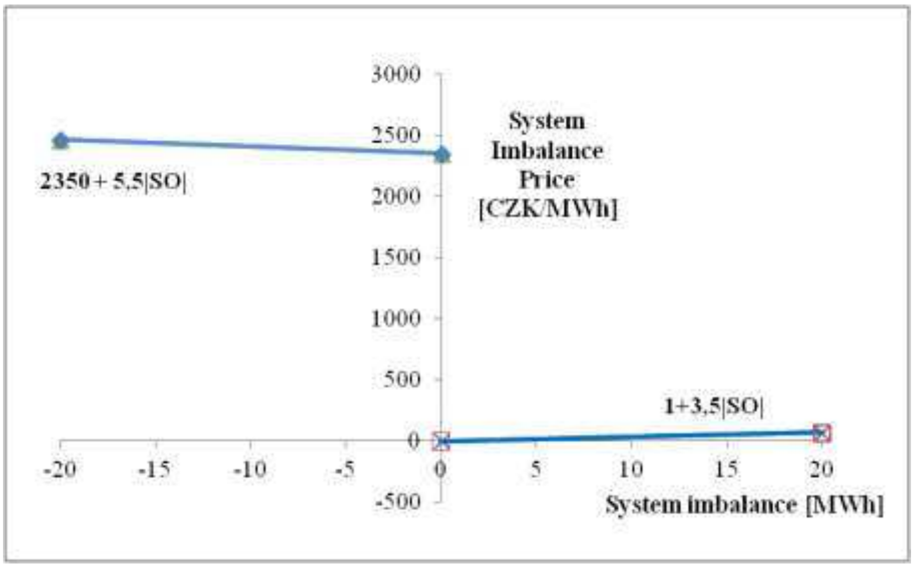
$$\boldsymbol{System\ imbalance} = \sum_{i=1} \boldsymbol{individual\ imbalance_i}$$

Equation 2.1

The subject of settlement pays for his imbalance only if his imbalance has the same direction as the system imbalance. If the imbalance of a subject of settlement is opposite to the direction of system imbalance (for example system imbalance is positive but individual imbalance is negative), the clearance subject is financially rewarded. If the subject creates the counter imbalance, it helps to get the grid back to stability.

The pricing of the system imbalance is set by the Czech Energy Regulatory office in such a way that the subjects of settlement have an incentive to minimize their own imbalance. The price they have to pay, if their imbalance has the same direction as the system imbalance, is the linear function of the system imbalance. Every subjects of settlement has to pay this price for each MWh of its individual imbalance, where the price is given by the function below. This price is applied to every MWh in the direction of the system imbalance.

Figure 2.3: System imbalance price



Source: OTE

The unit price of counter imbalance is the weighted average of regulatory energy obtained by CEPS. For the negative system imbalance the price is computed by averaging positive regulatory energy. In case of the positive imbalance it is the opposite case.

3. Methodology

We use hourly observations from the Czech electricity market from 2010 to 2014. Our dependent variable is the system imbalance. Its values are obtained from OTE’s website, which together with CEPS organize the regulatory energy market and together they determine the imbalance’s value for every hour. Other explanatory variable such as wind and solar output and load are taken from CEPS’s database.

To analyze the comovements of PV output and the system imbalance, we will apply ARMA-GARCH models. ARMA models contain two types of dependent variables. The first are lagged values of explanatory variables. The second ones are lagged values of residuals, which serve to correct the prediction of the model based on its past errors. Mean equation can be extended by other explanatory variables. On our case, we will add hourly and day of week dummies to represent the different patterns in electricity demand during the day. We will also add variables, which represent the current situation in the electricity market such as photovoltaic and wind production and overall load.

Our goal will be to investigate the significance of explanatory variables. This means that significant PV output would confirm the influence of the PV power plants on the size of the imbalance.

The autoregressive process is shown in the Equation 3.1. It consists of long-term mean, independent variables, which are lagged values of an explained variable and an error term. In order to be stationary the sum of all ϑ’s must be less than |1|. The basic representative is the AR(1) process with one lag.

$$\boldsymbol{SI_t = \mu + \sum_{i=1}^{p} \vartheta_t SI_{t-i} + u_t}$$

Equation 3.1

The moving-average process is shown in the Equation 3.2. MA processes is a family of process, where dependent variables are lagged error terms. To achieve stationarity the sum of all φ's must be less than |1|

$$\boldsymbol{SI_t = \delta + \sum_{i=1}^{p} \varphi_t u_{t-i} + u_t}$$

Equation 3.2

The ARMA(m,n) means usually that the process is described up m lagged AR terms and up to n lagged MA terms. However, we will label lags specifically. For example ARMA(1 2, 1 4) means that the first and the second lags are used for autoregressive terms and the first and the fourth lags are used for the MA terms.

We use the ARMA equation without the constant because ARMA process tends to revert to the central value in the long-term. In this particular case, when market agents are motivated to balance their own imbalance, the overall system imbalance tends to get to general balance between supply and demand in the market. The market participants are motivated to correctly predict their production and consumption so we set mean –equation to have a zero constant.

The GARCH(p,q) model is shown in the Equation 3.3. The conditional variance at time t h_t depends on the long-term variance (c_0), past values of variance and past values of prediction. Estimated coefficients have to be positive because the variance cannot be negative as it is the squared standard deviation. If the sum of all a's and b's is less than |1|, we can consider the GARCH model to be stationary.

$$h_t = c_0 + \sum_{i=1}^{p} a_i u_{t-i}^2 + \sum_{j=1}^{q} b_j h_{t-j}$$

Equation 3.3

There are many extensions to classical GARCH model. We will used TARCH model, which allows different behavior if the residual are negative to model the asymmetric effect. TARCH model is displayed in the Equation 3.4.

$$h_t = c_0 + \sum_{i=1}^{p} a_i u_{t-i}^2 + \sum_{j=1}^{q} b_j h_{t-j} + \sum_{i=1}^{p} \gamma_i I_{t-i} u_{t-i}^2$$

$$I_{t-1} = 1 \; if \; u_t < 0 \; and \; 0 \; otherwise$$

Equation 3.4

We will estimate the mean and the variance equations jointly using maximum likelihood estimate. The joint model is described in the Equation 3.5. If γ's=0 we have standard GARCH model.

$$\boldsymbol{SI_t = \sum_{i=1}^{m} \vartheta_t SI_{t-i} + \sum_{j=1}^{n} \varphi_t u_{t-j} + \beta_1 load + \beta_2 PV + \beta_3 wind + u_t}$$

$$h_t = c_0 + \sum_{i=1}^{p} a_i u_{t-i}^2 + \sum_{j=1}^{q} b_j h_{t-j} + \sum_{i=1}^{p} \gamma_i I_{t-i} u_{t-i}^2$$

$$I_{t-1} = 1 \; if \; u_t < 0 \; and \; 0 \; otherwise$$

$$u_t | F_t - 1 \sim N(0, h_t)$$

Equation 3.5

For comparing models we use Akaike information criterion (AIC) or Bayesian information criterion (BIC). Both are shown in the equations below. L stands for log-likelihood function, k for number of variables and B number of observations. The rule for choosing the right model is that the lower value of criterion suggests better model.

$$AIC = -2\ln(L) + 2k$$
$$BIC = -2\ln(L) + kln(N)$$

Equation 3.6

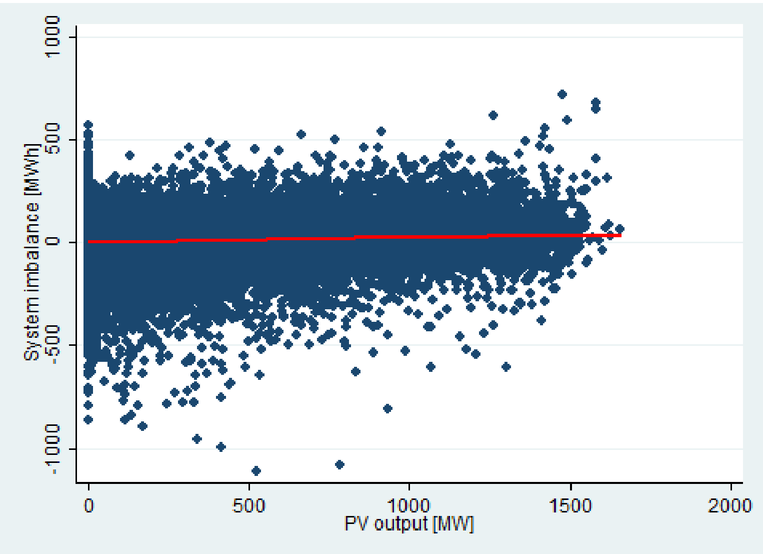
4. Photovoltaic production and the System Imbalance

In this section we will analyse the impact of production of solar power plants on the system imbalance of the Czech grid operated by CEPS. Ideally the whole grid should be in balance because the agents are motivated to indicate their production and consumption in advance.

Nevertheless CEPS has to deal with the system imbalance and it seems plausible that higher production from solar power plants could lead to higher fluctuations in system imbalance. Thus we believe this issue is worth of further investigation.

Before engaging in econometric modelling, we present several descriptive facts about the development of the Czech system imbalance.

Figure 4.1: Scatter plot PV output vs. System imbalance 2010-14



Source: OTE and CEPS

Scatter plot and fitted OLS line are displayed in the figure above. System imbalance is distributed around zero for all values of the PV production. The fitted line has positive slope but its magnitude is only 0.03. The correlation between variables is also positive and amounts to 0.09. This both pieces of information suggest that higher PV output could lead to more positive values of the system imbalance.

Table 4.1: Share of System imbalance types

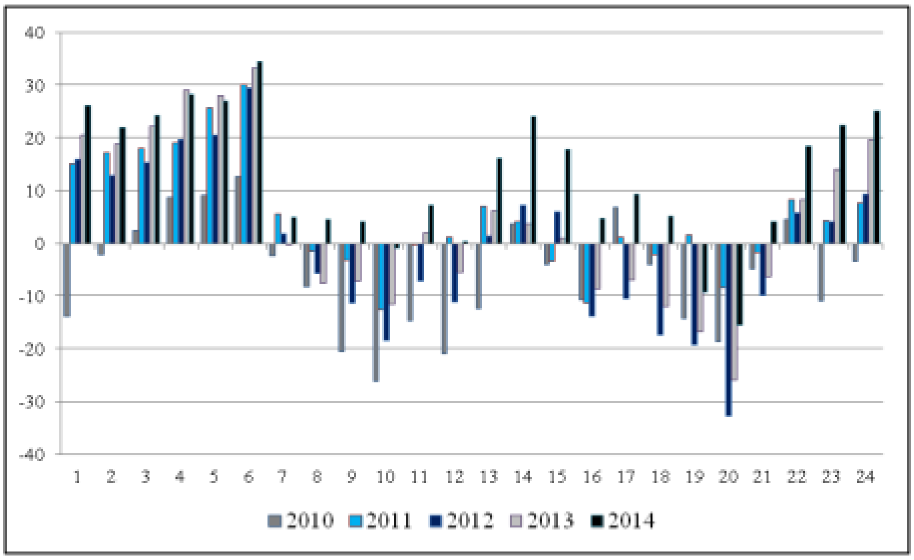
	2010	2011	2012	2013	2014	Total
Positive SI count	4 344	4 897	4 677	4 959	5 300	24 177
Negative SI count	4 416	3 863	4 107	3 801	3 460	19 647
Share of positive SI	49.6%	55.9%	53.2%	56.6%	60.5%	55.2%

Source: OTE and Authors computations

Frequency of different types of imbalances are shown in the Table 4.1. In 2010 there was higher share of negative imbalances than positive ones. Nevertheless, in the following years when the production from photovoltaic power plants increased, positive imbalances started to prevail. The share increased to 60 % in 2014.

The graph below presents the hourly averages of system imbalance. Obviously the system imbalance tends to be positive in very early morning hours and late evening hours. These are hours, when the consumption is lowest.

Figure4.2: System imbalance hourly averages 2010-2014



Source: OTE and Authors computations

Descriptive statistics are shown in the table below. The system imbalance was negative in 2010 but in other years it was either positive or very close to zero as in 2012. Years starting 2011 exhibit higher solar production as compared to 2010. Another noteworthy thing is lower standard deviation in 2014, which means that system imbalance values were more concentrated around zero. Positive media values are in line with prevailing occurrences of positive system imbalance as shown before in this section.

Table 4.2: Descriptive statistics of system imbalance 2010-2014

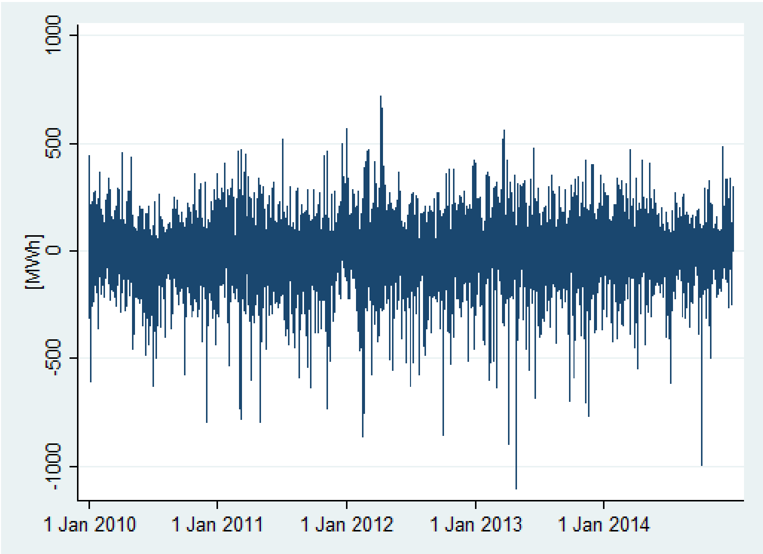
MWh	2010	2011	2012	2013	2014
Mean	-6.61	5.04	-0.37	4.07	12.68
Median	-0.60	10.40	6.06	11.40	15.01
Sample standard deviation	104.82	107.43	107.78	107.85	88.29
Minimum	-794.10	-795.79	-861.10	-1 108.19	-996.79
Maximum	457.30	520.01	720.21	557.71	484.10

Source: OTE and Authors computations

4.1. ARMA-GARCH model estimation

First we will fit the right ARMA-GARCH model which we will use as a baseline. Then we augment the baseline model by additional variables such as time dummies and also production. Then we will decide, which model better fits the data process. If we observe that by adding photovoltaic production to the model, the model delivers better performance, we conclude that PV production has statistically significant effect on the level of system imbalance. This approach is motivated by the work done by (Efimova & Serletis, 2014), who published a paper on modelling of energy markets with a section devoted to modelling of electricity prices.

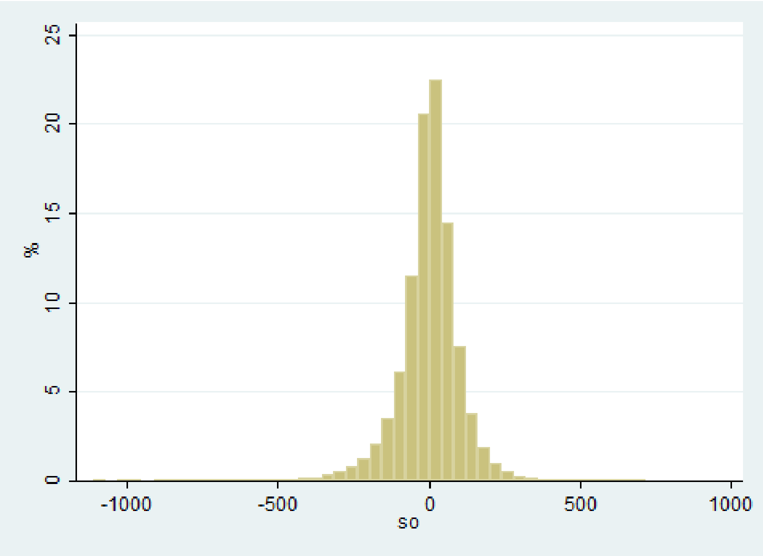
Figure 4.3: System imbalance 2010-2014



Source: OTE

Figure 4.3 contains the development of the system imbalance in the last five years. The time series is concentrated around zero, which is given by the fact that market participants are motivated to keep their own imbalances close to zero. The series shows some clustering and also several spikes in some hours. Augmented Dickey-Fuller test rejects the null hypothesis of unit root's presence so the series can be treated as integrated of order zero and we do not have to difference it.

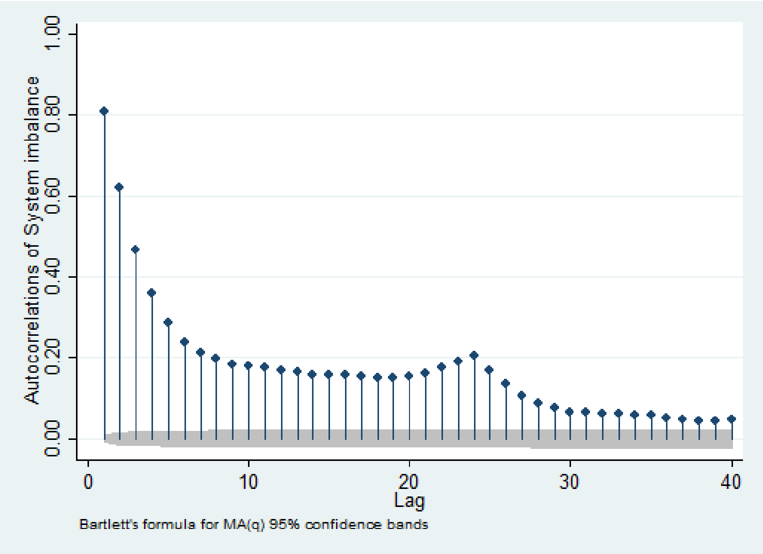
Figure 4.4: System imbalance 2010-2014 histogram



Source: OTE

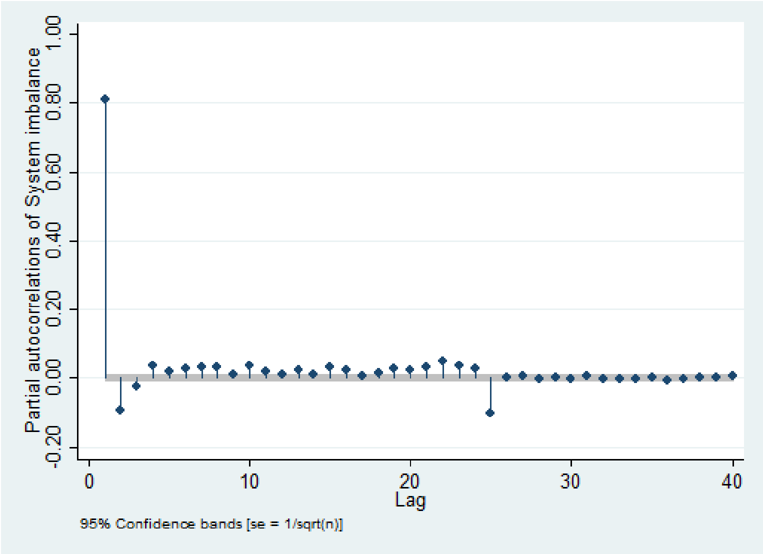
Histogram of system imbalances over the five-year period is shown in the Figure 4.4. The distribution of system imbalances is concentrated around zero and it is slightly negatively skewed. The distribution is also steeper around the mean value that normal distribution. Its leptokurtic nature is confirmed by the precise calculation.

Figure 4.5: Autocorrelations of System imbalance



Source: Authors computations

Figure 4.6: Partial autocorrelations of System imbalance



Source: Authors computations

Figures above display autocorrelation and partial autocorrelation functions of system imbalance. The autocorrelation function is gradually decaying, whereas in the case of partial autocorrelation the first lag is significantly larger than others. According to (Horváth, 2015) such correlograms would imply AR(1) process but after fitting the process on our data the residuals were not white noise.

Therefore we had to investigate the fit for other forms of ARMA processes. To decide, which specification will be chosen, Akaike information criterion and Bayesian information criterion are chosen. Both criteria prefer ARMA(1 2, 1 2). The graphs displaying autocorrelations and partial autocorrelations functions for this model are given down here.

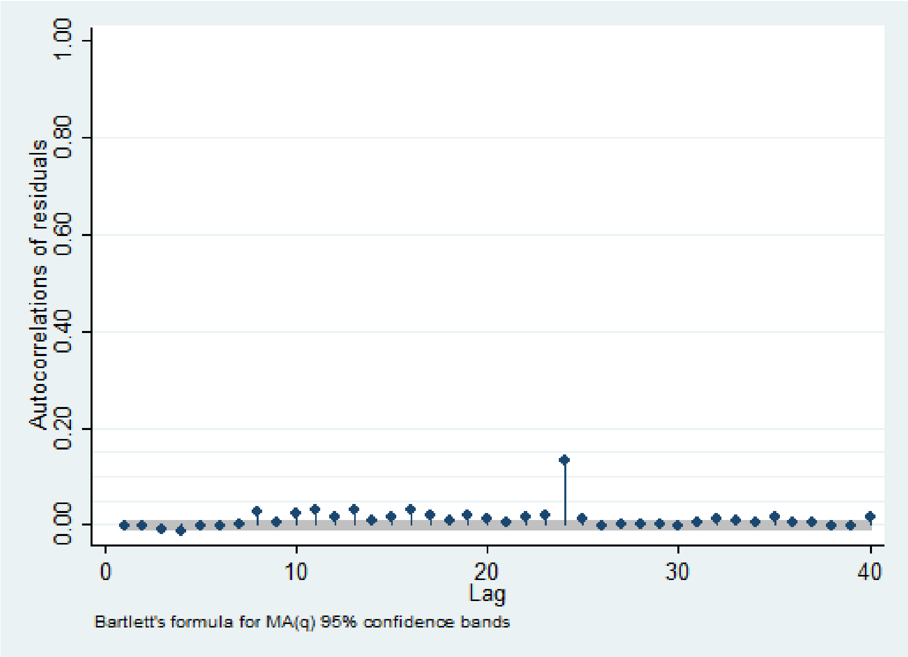
Both autocorrelations and partial autocorrelations are insignificant for first 7 lags. Other coefficients are not high as well. The only exception in both cases is the twenty-fourth lag because the market conditions were probably similar 24 hours ago. Based on this finding we trid to fit also ARMA(1 2 24, 1 2 24) model, which delivers better performance based on both criteria. However, in order to keep our model parsimonious we decided to stay with ARMA(1 2, 1 2) model.

Table 4.3: Information criteria

MWh	AIC	BIC
ARMA(1,0)	484 608	484 634
ARMA(0,1)	502 933	502 959
ARMA(1,1)	484 263	484 297
ARMA(1 2,1)	484 224	484 267
ARMA(1,1 2)	484 189	484 232
ARMA(1 2,1 2)	484 178	484 230
ARMA(1 2 24, 1 2 24)	483 462	483 532

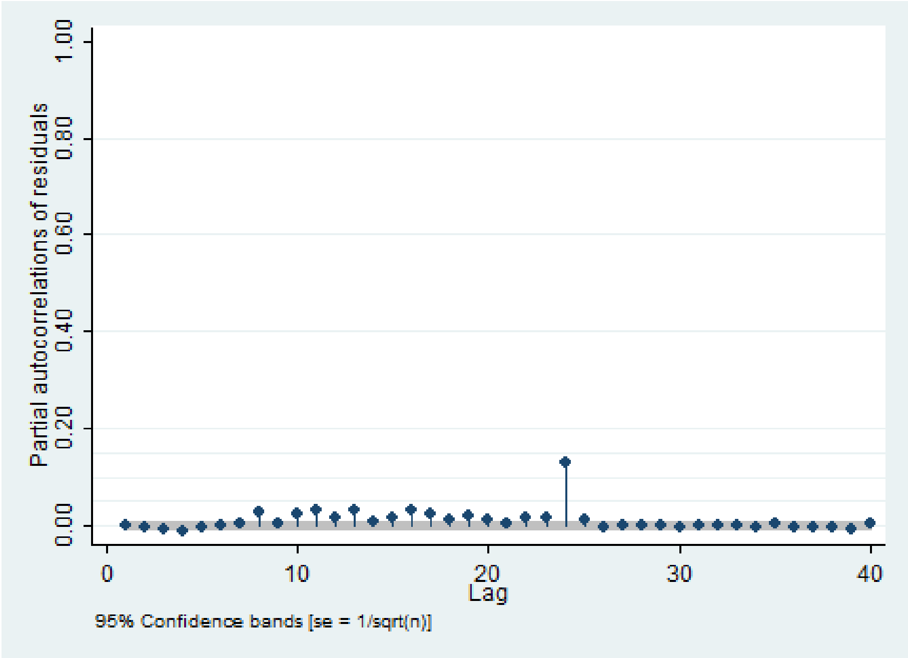
Source: Authors computations

Figure 4.7: Autocorrelations of ARMA(1 2,1 2) residuals



Source: Authors computations

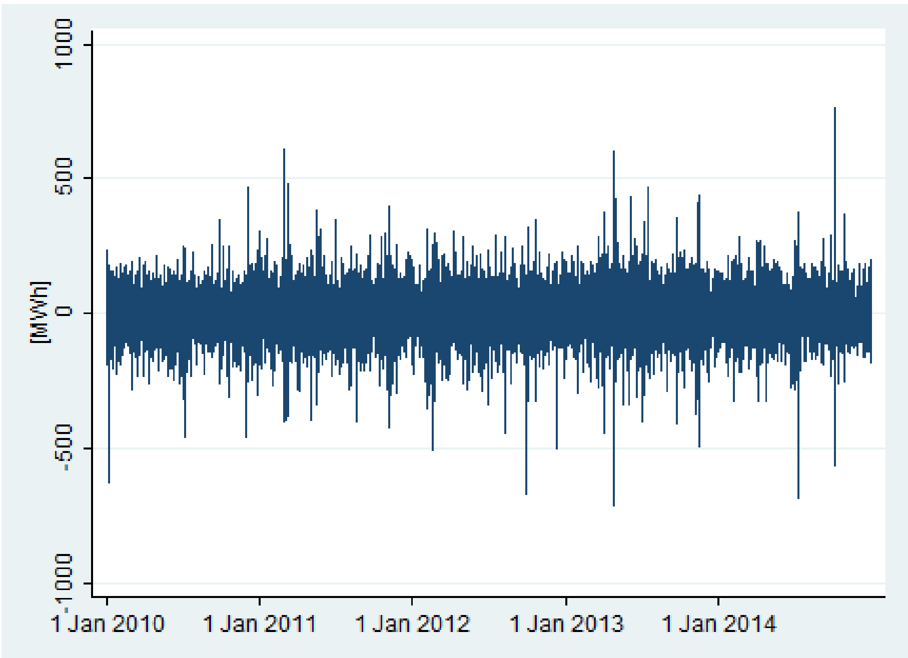
Figure 4.8: Partial autocorrelations of ARMA(1 2,1 2) residuals



Source: Authors computations

As the next step, we investigate, whether ARCH effects are present in the residuals. The residuals are shown in the Figure 4.9. It appears that there might be some presence of volatility clustering so we proceed to econometric test.

Figure 4.9: ARMA(1 2,1 2) model residuals



Source: Authors computations

Results of ARCH-LM test are shown in the Table 4.4. The regression unequivocally rejects the presence of no ARCH effects in residuals because all lagged squared residuals are statistically significant and all of them together are jointly significant as well. Correlograms of squared residuals can be found in Figure 4.10 and Figure 4.11. Both figures decay so according to (Horváth, 2015) GARCH(1,1) model is fitted. The behavior of residuals shows that this specification is the correct one.

Table 4.4: ARCH-LM test

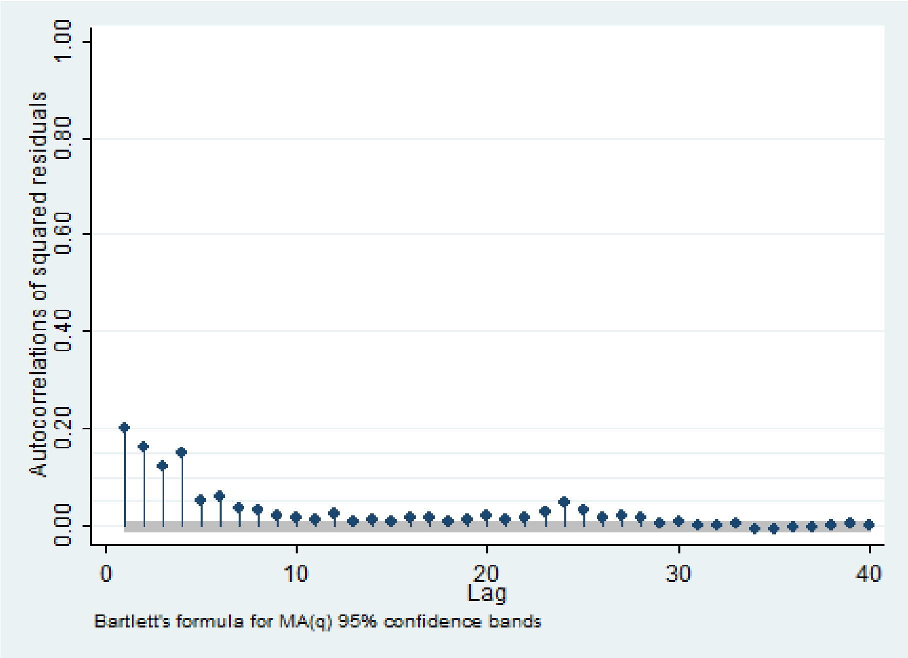
Explained variable	Squared residuals$_t$
Squared residuals$_{t-1}$	0.161***
	(0.005)
Squared residuals$_{t-2}$	0.104***
	(0.005)
Squared residuals$_{t-3}$	0.056***
	(0.005)
Squared residuals$_{t-4}$	0.104***
	(0.005)
Squared residuals$_{t-5}$	-0.016***
	(0.005)
Constant	2 175.249***
	57.52
Prob>F(5,43 813)	0.00

Note: Standard errors reported in parenthesis.

*(p < 0.1) **(p < 0.05) ***(p < 0.01).

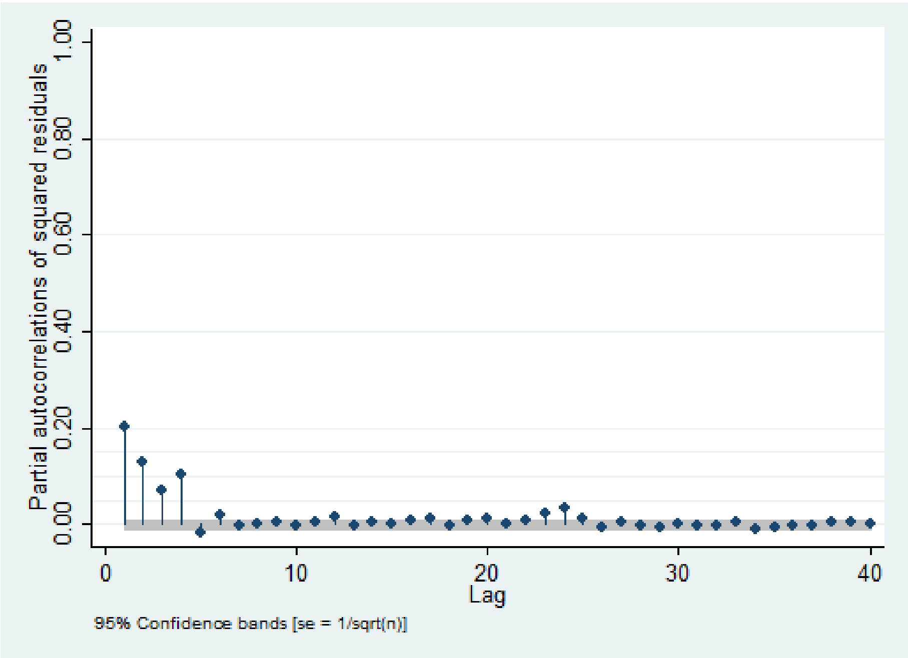
Source: Authors computations

Figure 4.10: Autocorrelations of ARMA(1 2,1 2) squared residuals



Source: Authors computations

Figure 4.11: Partial autocorrelations of ARMA(1 2,1 2) residuals



Source: Authors computations

Table 4.5 contains the results of regressions. We ran several specifications to ensure that our results are robust. Firstly, we estimated the basic ARMA-GARCH model and then we added other explanatory variables. The explanatory variables that were consecutively added are photovoltaic and wind output, load and time dummy variables.

Results suggest that PV production has statistically significant effect on the size of the system imbalance. The higher is the output, the more positive is the system imbalance. It means that when the PV output is high on average the grid operator has to deal with excess supply of electricity and has to decrease output elsewhere.

As far as the wind output is concerned, the same rationale holds. This is expected behavior with respect to the intermittent nature of both sources. On the other hand, the higher is the load, the more negative is system imbalance. This result could be expected as well because high demand could induce the lack of power supplied to the grid.

Table 4.5: ARMA-GARCH models results

	Model S1	Model S2	Model S3	Model S4
	SI$_t$	SI$_t$	SI$_t$	SI$_t$
	2010-14	2010-14	2010-14	2010-14
Load$_t$			-0.002***	-0.006***
			(0.000)	(0.001)
Wind$_t$			0.457***	0.482***
			(0.024)	(0.024)
PV$_t$		0.090***	0.092***	0.095***
		(0.003)	(0.003)	(0.003)
AR L1	0.374***	0.244**	0.245**	0.242**
	(0.107)	(0.109)	(0.108)	(0.108)
AR L2$_t$	0.261***	0.379***	0.374***	0.380***
	(0.080)	(0.084)	(0.082)	(0.083)
MA L1	0.452***	0.578***	0.578***	0.577***
	(0.107)	(0.109)	(0.108)	(0.108)
MA L2	0.072***	0.064***	0.064***	0.063***
	(0.009)	(0.007)	(0.007)	(0.007)
Hourly dummies		Yes	Yes	Yes
Daily dummies	No	Yes	Yes	Yes
Monthly dummies	No	No	No	Yes
Constant	893.782***	868.782***	867.583***	867.200***
	(18.164)	(17.944)	(17.721)	(17.889)
ARCH L1	0.267***	0.264***	0.269***	0.267***
	(0.004)	(0.005)	(0.005)	(0.005)
GARCH L1	0.500***	0.501***	0.496***	0.496***
	(0.007)	(0.007)	(0.007)	(0.007)
Observations	43 824	43 824	43 824	43 824

Source: Authors computations

Explanatory variables added to the equation had significant effect on the magnitude of the system imbalance. In the next step we will add variables also to the variance equation to test whether the production of renewable energy had the impact on the volatility.

The variables added to the variance equation are load, PV and wind output and also time dummies. Variables used in the variance equation are the same ones as in the mean one.

The Table 4.6 contains the results of GARCH analysis. The regression was launched for the whole sample and also for each year separately. Firstly, some coefficients are negative in some years in the variance equation but all fitted values of the conditional variance are positive so this issue does not pose a problem for us.

Before investigating the variance equation, the economic significance of the impact of the PV production on the size of the system imbalance will be discussed. The coefficients in last four years are estimated between 0.044 and 0.062. Average solar output during peak hours of the same period is 434 MW. Average system imbalance amounts to 3 MWh so we draw a conclusion that solar production has substantial effect on the size of imbalance and pushes it to the positive values.

However, positive system imbalance is better alternative that the negative one because it requires only the decrease of current output by adjusting dispatchable source, which is less costly than increasing it.

Despite the statistical significance of PV coefficients in the variance equation, photovoltaic production does not appear to have economically significant effect on the conditional variance. Coefficients of PV output in last four years, which is a period of stable solar production, lie between 0.0002 and 0.0007. The maximal solar output in one single hour over the five year period was 1 656 MWh. Multiplying previous two figures and comparing the result with five-year sample variance equal to 10 754, we conclude that the solar production does not have a substantial impact on the volatility of the system imbalance in the Czech Republic.

Table 4.6: ARMA-GARCH models results – the volatility study

	Model SV1	Model SV2	Model SV3	Model SV4	Model SV5	Model SV6
	SI_t	SI_t	SI_t	SI_t	SI_t	SI_t
	2010-14	2010	2011	2012	2013	2014
$Load_t$	-0.003***	-0.004***	-0.004***	-0.003***	-0.003***	-0.003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$Wind_t$	0.545***	0.453***	0.654***	0.516***	0.546***	0.543***
	(0.023)	(0.067)	(0.051)	(0.066)	(0.064)	(0.040)
PV_t	0.060***	0.329***	0.062***	0.059***	0.052***	0.044***
	(0.002)	(0.037)	(0.006)	(0.005)	(0.005)	(0.004)
AR L1	0.288**	0.412	0.492**	0.545**	0.533**	0.556***
	(0.118)	(0.282)	(0.209)	(0.242)	(0.251)	(0.029)
AR $L2_t$	0.342***	0.332	0.187	0.115	0.120	0.112***
	(0.090)	(0.235)	(0.161)	(0.178)	(0.182)	(0.024)
MA L1	0.526***	0.391	0.353*	0.308	0.241	-0.795***
	(0.118)	(0.282)	(0.208)	(0.243)	(0.251)	(0.032)
MA L2	0.059***	0.024	0.076***	0.071**	0.059***	-0.104***
	(0.007)	(0.018)	(0.018)	(0.031)	(0.016)	(0.017)
Hourly dummies	Yes	Yes	Yes	Yes	Yes	Yes
Daily dummies	Yes	Yes	Yes	Yes	Yes	Yes
Monthly dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.657***	5.634***	6.664***	5.448***	6.386***	5.582***
	(0.000)	(0.116)	(0.093)	(0.099)	(0.079)	(0.104)
$Load_t$	0.0002***	0.0002***	0.0002***	0.0002***	0.0000***	0.0002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$Wind_t$	0.0002***	-0.0003	-0.0009**	-0.0036***	0.0039***	0.0021***
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
PV_t	0.0005	-0.003***	0.0002**	0.0005***	0.0007***	0.0007***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ARCH L1	0.267***	0.222***	0.293***	0.274***	0.261***	0.292***
	(0.004)	(0.013)	(0.014)	(0.011)	(0.009)	(0.008)
GARCH L1	0.422***	0.525***	0.317***	0.386***	0.451***	0.296***
	(0.007)	(0.021)	(0.021)	(0.019)	(0.013)	(0.021)
Hourly dummies	Yes	Yes	Yes	Yes	Yes	Yes
Daily dummies	Yes	Yes	Yes	Yes	Yes	Yes
Monthly dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	43 824	43 824	43 824	43 824	43 824	43 824

Source: Authors computations

5. Conclusions

In this paper we provided a brief introduction to the topic of photovoltaics production and its electricity grid integration in the Czech Republic. In the analytical part of this paper we focused on the determination of the effect of photovoltaic energy on the size and the volatility of the Czech electricity grid system imbalance. To our knowledge, this is one of the first studies dealing with the electricity system imbalance in the Czech Republic.

Our GARCH models suggest that both size and volatility of Czech system imbalance are statistically significantly influenced by renewable energy resources, mainly by solar electricity. However only the size effect is significant in economics terms. The impact on volatility was not economically important.

Still, this conclusion about volatility does not suggest that intermittent production is not a challenging issue for the regulator, transmitter and other agents. The results rather indicate that the current setup of the Czech market with regulatory energy motivates market participants to mitigate risks associated with their demand and supply. Investigating particular investments that were made by market agents in order to optimize their economic performance under existing and anticipated electricity market regulation environment is an important and challenging issue for further research.

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