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AN ECONOMETRIC MODEL OF HOUSEHOLD ELECTRICITY CONSUMPTION. A CASE STUDY OF POLAND

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Purpose: Electrical energy is in this day and age fundamental to the functioning of every household. The use of gas, heating oil or solid fuels for home heating also involves the supply of electricity. Today, electric power is the most environmentally friendly source of energy. Experience has shown that substitution of an oil heating system with a heat pump resulted in significant financial savings for the household.
Design/methodology/approach: The purpose of this paper shall entail the construction of a multi-equation econometric model describing the mechanisms of electricity consumption in a specified household. The model takes the nature of a system of interdependent equations. Described shall be the monthly volume of electricity consumption, payment amount of for this energy (in PLN), and price per 1 MWh in a given month. Monthly time series from September 2015 to November 2022 have been used, which resulted in a time series with a count of 87 statistical observations.
Findings: The econometric model of household electricity consumption presented in this paper confirms both the hypothesis about feedback between the variables USAGE and PRICE as well as the recursive effect of electricity consumption volume on its value in monetary units. In addition to the cognitive value of the econometric modeling results obtained, the empirical tool constructed makes enables forecast estimation of the energy consumption volume, its value and unit price in subsequent months, for at least 12 consecutive months.
Practical implications: This type of research has great practical utility. They make it easier for rational interaction between electricity sellers and specific consumers.
Social implications: Knowledge about the mechanisms of electricity consumption on the farm home may influence the rationalization of consumption and spending. This type of rationalization should have a positive impact on the environment natural, contributing to the reduction of greenhouse gas emissions.
Originality/value: The novelty and originality of the work are the identification of the mechanism behavior of a single household consuming energy electric. Feedback between magnitudes revealed electricity consumption and its price on a specific farm home. The recipients of the work will be electricity sellers, consumers, and researchers of household market behavior.

Keywords: econometric model, electricity consumption, interdependent equations.

Category of the paper: Research paper. Case study.

1. Introduction

The use of energy sources underpins human life. Currently, by far the most important of household energy sources is electricity. In fact, there are households where electricity constitutes the only source of power. It is worth paying attention to the ongoing energy transformation. There is a shift away from fossil energy sources such as: oil, gas, or coal. Renewable energy sources play an increasingly important role. The presented household is in line with this trend.

The decarbonization of the Polish economy will cause increased household demand for electricity. At the same time, rising energy prices will correct demand, which will result in a negative feedback between the price and its consumption.

The purpose of this paper entails the construction of a multi-equation microeconometric model describing the mechanisms of electricity consumption in a specified household. The model takes the nature of a system of interdependent equations. Described shall be the monthly volume of electricity consumption, payment amount for this energy (in PLN), and 1 MWh rate in a given month. Monthly time series from September 2015 to November 2022 have been used. The resulting time series has a count of 87 statistical observations.

The work has an original character, presenting the case of a specific household. In this household, electricity is the only source of energy. There is a lack of such research in the literature due to unavailability of statistical data regarding the consumption of electricity in specific households.

2. Literature Review

Household electricity consumption has been the subject of many scientific papers. The period from 2016 onward is marked by articles addressing the issues of household electricity consumption analysis by means of ordered logit models, i.e., the example of Turkey (Ari, Aydin, Karacan, Saracli, 2016). One of the articles worth noting deals with the analysis of electricity consumption behavior, based on a case study of a non-business household in Malang (Karisma, Maski, Noor, 2016). The impact of geodemographic factors on electricity consumption and forecasting models has also been addressed in the subject literature (Singh, Alam, Yassine, 2016). Another paper discusses the econometric modeling of household electricity consumption as a tool in calculating the social norm of consumption (Zaitseva, Yu, 2016). Case study investigation of the energy savings resulting from fan coil speed control based on the number of persons (Hernández-Tabares, 2017) represents an important focus as well. Yet another noteworthy paper entitled *Disentangling household and individual actors in* *explaining private electricity consumption* concerns individual electricity consumption (Seebauer, Wolf, 2017). Hidalgo J., Coello S., Mg., González Y. (2018), in turn, have addressed the subject of electricity demand factors in Marginal Ecuador, through a case study of Monte Sinai. M.J. Kim (2018), in contrast, presents the characteristics and determinants of household electricity consumption in Korea. A paper by Ali S.S.S., Razman M.R., Awang A. (2020) tackles the topic of estimating household electricity consumption and appliance ownership in a Malaysian intermediate city. *Determinants of household electrical energy consumption: Evidences and suggestions with application to Montenegro* constituted the subject of research by Đurišic´ V., Rogic´ S., Smolovic´ J.C., Radonjic´ M. (2020). In Greece, a study of the sociodemographic determinants of household electricity consumption was conducted using quantile regression analysis (Kostakis, 2020). A Nigerian example can be found in a paper (Mamudu, Ochei, 2020), in which an empirical analysis of electricity consumption, in relation to the economic growth in Nigeria, was undertaken. Non-linear analysis of the effect of electricity price on household electricity consumption constituted the subject of research in an article by Zhang L., Wen X. (2021). Finally, a comparison was made of energy consumption in American households, in distribution by climate region (Debs, Metzinger, 2022).

As the above literature review shows, researchers have taken a significant interest in various aspects of household electricity consumption. Nevertheless, further research into the topic so essential to the operation of each household, regardless of its location, is still needed.

3. Methodology and Data

The paper shall attempt to describe the mechanism of household electricity consumption volatility in monthly terms, from September 2015 to November 2022. The household is located in Toruń (Poland). It covers a land area of roughly 6000 m^2, with a house of approx. 300 m^2, a 60 m^2 detached garage, and an outbuilding of circa 450 m^2. The only energy source used in this household is electricity, obtained exclusively from the power grid. There is no use of gas. Up until March 2021, the house had been heated with fuel oil. In April 2021, the oil furnace was replaced with a heat pump. Electricity is thereby used for the heating and lighting of the residential dwelling and the garage, for cooling, as well as for utility and land-irrigation ground water intake.

The paper shall describe the mechanism of electricity consumption, described by a system of interdependent equations. The volatility thereof shall be considered both quantitatively as well as in value, including analysis of the 1 MWh unit price dispersion, i.e.:

$$\text{USAGE} \begin{array}{l} \nearrow \text{VALUE} \\ \leftrightarrow\!\searrow \text{PRICE} \end{array} \tag{1}$$

where USAGE represents the volume of monthly electricity consumption, VALUE is the monthly cost of electricity consumption in PLN, and PRICE indicates the unit price per 1 MWh, in PLN. Formula (1) shows that the volume of electricity consumption directly affects its cost to the household and the unit price. Simultaneously, the unit price of energy exerts impact on the volume of energy consumption. This means that the variables USAGE and PRICE form a feedback loop, i.e.:

$$\text{USAGE} \rightleftarrows \text{PRICE} \tag{2}$$

Negative feedback of the above pair of variables can be expected. An increase in energy consumption results in a unit price decrease, while an increase in the unit price induces a decrease in electricity consumption.

The process of household electricity consumption shall be described by three stochastic equations. Each equation's parameters shall be estimated using the ordinary least squares method. The reasons for this estimation approach have been described in the work of Wisniewski J.W. (2022). Autoregressions, lags of endogenous variables, a trend and monthly periodic fluctuations are taken into account in the model equations. A model such as this can be used to forecast endogenous variables using an iterative method, as described in the work of Wisniewski J.W. (2021, 2016, subsection 2.5, 2023, subsection 2.4).

4. Results and Discussion

In the period from 2015 to 2020, seasonal oscillations occurred in the volume of electricity consumption and the amount of its value in the household under consideration. After the abandonment of the oil-fired heating system for the house and domestic water supply, and the installation of a heat pump, a sharp increase in the magnitude of the variables USAGE and VALUE occurred. This is illustrated in Figures 1 and 2. In the period from 2015 to 2019, a stabilization of the energy unit price is also observed. A price spike occurred in March 2000. The unit price fluctuated since then, with a slight tendency to rise steadily. This process is illustrated in Figure 3, showing the fluctuations in the variable PRICE. Unit prices for household electricity ranged from PLN 607.89 to PLN 740.90 per MWh.

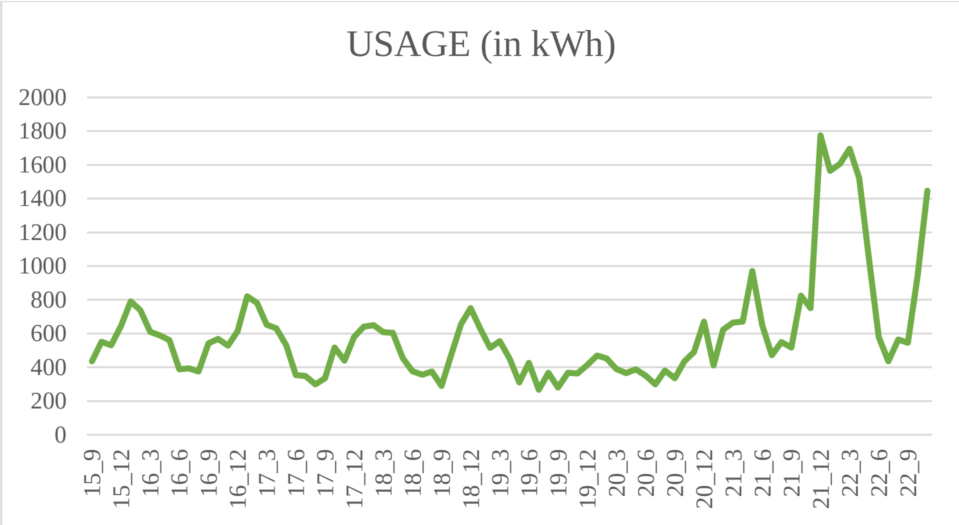

Figure 1. Monthly household electricity consumption in the period 2015.09 – 2022.11.

Source: ENERGA invoices.

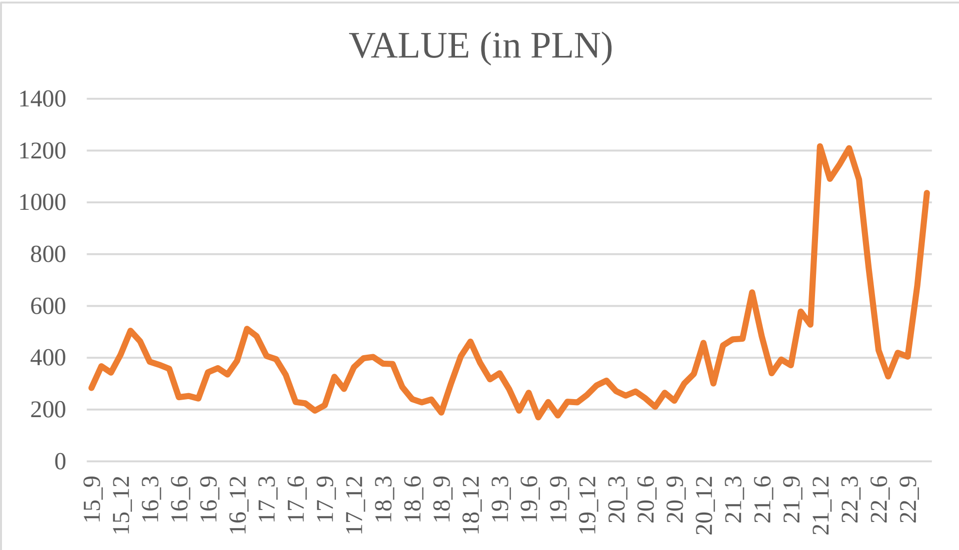

Figure 2. Value of monthly household electricity consumption in the period 2015.09 – 2022.11 (in PLN).

Source: ENERGA invoices.

Parameters of three stochastic equations forming the household electricity consumption system were estimated (Table 1). The first of the empirical equations presents the mechanism of electricity consumption. The unit price of electricity plays an important role in this equation. An increase in the concurrent price of electricity reduces the volume of energy consumption. As such, the classic mechanism of a decrease in demand under the influence of a unit price increment is at work here. The impacts of the price lagged by 1, 6 and 7 months are statistically significant as well. They are corrective in nature for electricity consumption, with lags of 1 and 6 months adjusting consumption positively, and a lag of 7 months triggering a negative adjustment of consumption under the influence of the unit price increment.

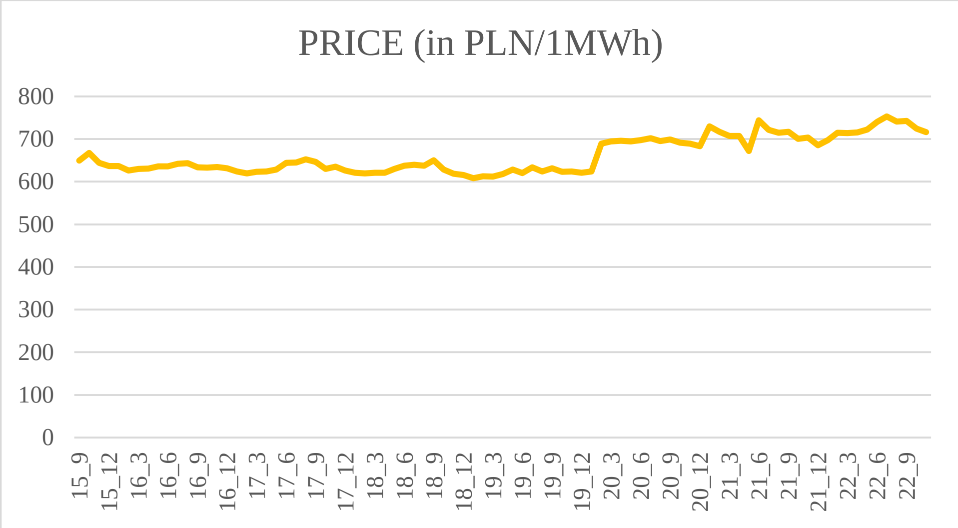

Figure 3. Prices per 1 MWh of household electricity in the period 2015.09 – 2022.11 (in PLN/1MWh).

Source: own calculation.

Table 1.
Dependent variable: USAGE, observations used 2016.05-2022.11 (N = 79)

Variable	Coefficient	Std. Error	t-Statistic	Prob. p	Significance
const	−197.952	281.559	−0.7031	0.4844	
PRICE	−4.51717	0.855759	−5.279	<0.0001	***
PRICE_1	3.67887	0.984763	3.736	0.0004	***
PRICE_6	3.78387	0.933031	4.055	0.0001	***
PRICE_7	−2.36990	0.913559	−2.594	0.0116	**
PUMP	366.607	61.0021	6.010	<0.0001	***
USAGE_1	0.670004	0.0666205	10.06	<0.0001	***
USAGE_4	0.205710	0.0889041	2.314	0.0237	**
USAGE_5	−0.330384	0.0852801	−3.874	0.0002	***
USAGE_8	0.124633	0.0555391	2.244	0.0280	**

Mean dependent var.	598.5063	S.D. dependent var.	332.7467
Sum squared resid.	770585.7	S.E. of regression	105.6783
R-squared	0.910772	Adjusted R-squared	0.899134
F(9, 69)	78.25599	Prob(F-statistic)	1.17e-32
Log likelihood	−474.9217	Akaike info criterion	969.8435
Schwarz criterion	993.5380	Hannan-Quinn criterion	979.3362
Autocorrel. coeff. (rho1)	−0.126826	Durbin h-statistic	−1.398861

Source: Own calculations using the GRETL package.

A dummy variable (PUMP) occurs in the equation of electricity consumption, taking the value of 1 in the months after the heat pump had been installed and 0 in the entire preceding period. This means that the use of the heat pump increased the household's electricity consumption by an average of 366.6 kWh per month. It is evident from this that the heat pump triggered an increase in the household electricity consumption by nearly 4400 kWh per year. The replacement of the oil-fired furnaces and boilers with a heat pump resulted in a significant cost reduction. The empirical equation in question shows autoregressive correlations: positive of 1, 2 and 8 months, and corrective negative of 5 months. The actual electricity consumption and the theoretical values obtained from the empirical model are graphically illustrated in Figure 4.

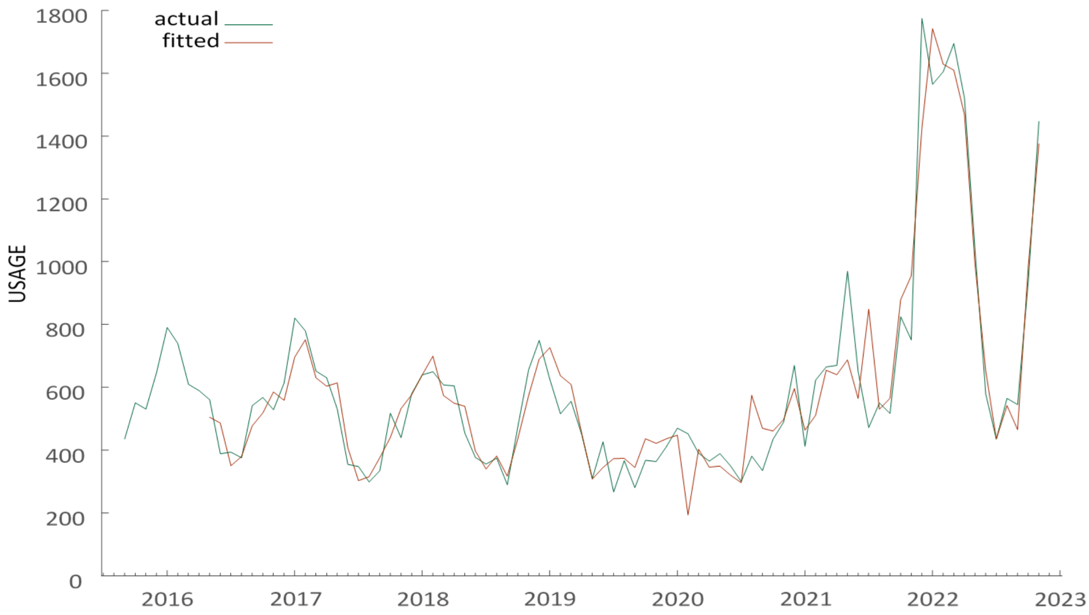

Figure 4. Actual and fitted values of variable: USAGE.

Source: Own calculations using the GRETL package and Table 1.

Table 2 shows the empirical equation describing the volatility of monthly electricity consumption value. Recursive effect of the energy consumption volume on its value comes into play here. A concurrent unit increase in energy consumption causes an increase in its value by approx. 652 PLN per 1 MWh. Negative adjustments with lags of 1 and 8 months simultaneously arise. The equation also shows a positive autoregression with periods of 1 and 8 months. The sequential reference from the 1-month period is of particular significance. It means that more than 74% of the previous month's value is revealed in the current value of household electricity consumption. Slight negative autoregressive adjustments of the variable VALUE, with lags of 5 and 12 months, likewise occur. The equation's explanatory variables explain the volatility of nearly 99.9% of the variable's (VALUE) formation mechanism. Graphical illustration of the actual electricity consumption values and the theoretical values obtained from the empirical model is presented in Figure 5.

Table 2.

Dependent variable: VALUE, observations used 2016.09-2022.11 (N = 75)

Variable	Coefficient	Std. Error	t-Statistic	Prob. p	Significance
const	10.8832	4.37675	2.487	0.0154	**
USAGE	0.652252	0.00672407	97.00	<0.0001	***
USAGE_1	−0.468964	0.0416847	−11.25	<0.0001	***
USAGE_8	−0.224058	0.0454904	−4.925	<0.0001	***
VALUE_1	0.743339	0.0610527	12.18	<0.0001	***
VALUE_5	−0.0205559	0.00711779	−2.888	0.0052	***
VALUE_8	0.355201	0.0673714	5.272	<0.0001	***
VALUE_12	−0.0420434	0.0132410	−3.175	0.0023	***

Cont. table 2.

Mean dependent var.	408.3923	S.D. dependent var.	244.3413
Sum squared resid.	4567.269	S.E. of regression	8.256403
R-squared	0.998966	Adjusted R-squared	0.998858
F(7, 67)	9249.036	Prob(F-statistic)	2.13e-97
Log likelihood	−260.5147	Akaike info criterion	537.0295
Schwarz criterion	555.5694	Hannan-Quinn criterion	544.4323
Autocorrel. coeff. (rho1)	−0.185294	Durbin h-statistic	−1.890566

Source: Own calculations using the GRETL package.

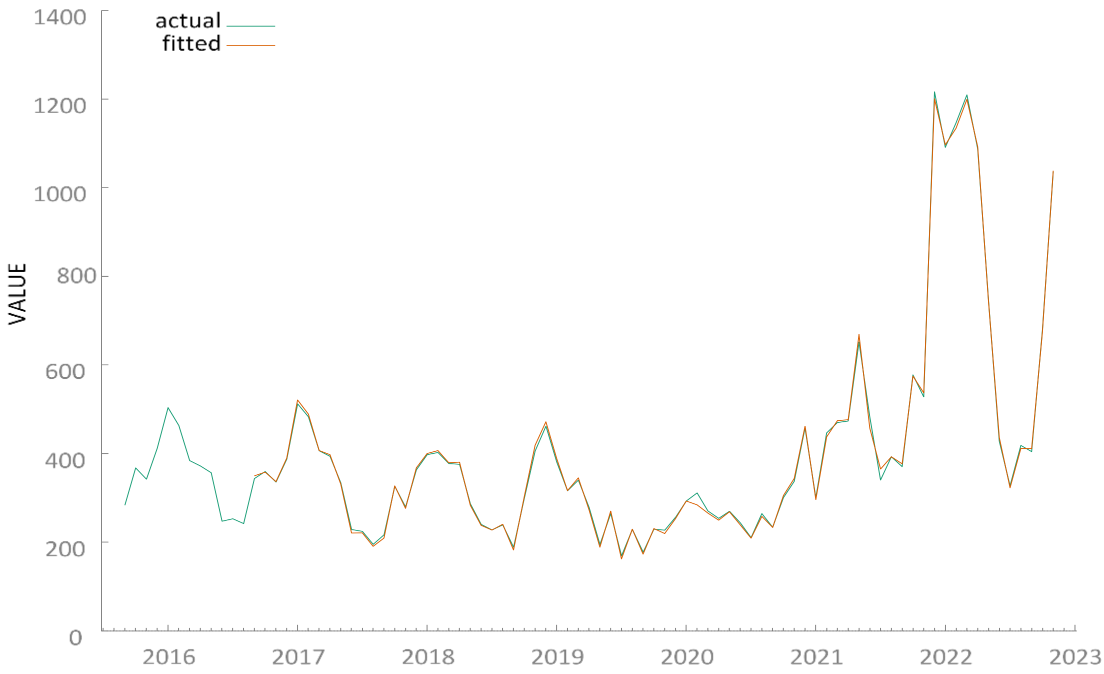

Figure 5. Actual and fitted values of variable: VALUE.

Source: Own calculations using the GRETL package and Table 2.

Table 3 illustrates the empirical equation of monthly electricity unit price in the household under analysis. The hypothesis about a feedback loop between the variables PRICE and USAGE has been confirmed. An increase in electricity consumption results in a simultaneous decrease in the price per 1 MWh. The relatively high fixed costs in the unit price are distributed over a greater number of units of energy consumed. This results in a decrease in the unit price per 1 MWh. The equation also shows positive adjustments to the unit price every 1 and 6 months and a negative adjustment with a lag of 5 months.

Table 3.
Dependent variable: PRICE, observations used 2016.09-2022.11 (N = 75)

Variable	Coefficient	t-Statistic	Prob. p	Significance
const	55.7383	1.199	0.2349	
USAGE	−0.0550942	−7.052	<0.0001	***
USAGE_1	0.0585181	6.798	<0.0001	***
USAGE_5	−0.0409556	−4.245	<0.0001	***
USAGE_6	0.0340014	3.560	0.0007	***
TIME	0.276738	2.400	0.0192	**
PRICE _1	0.842834	12.60	<0.0001	***
PRICE _11	0.353386	3.348	0.0013	***
PRICE _12	−0.294481	−2.660	0.0098	***

Mean dependent var.	664.9519	S.D. dependent var.	43.65533
Sum squared resid.	8434.964	S.E. of regression	11.30498
R-squared	0.940190	Adjusted R-squared	0.932940
F(8, 66)	129.6858	Prob(F-statistic)	2.57e-37
Log likelihood	−283.5199	Akaike info criterion	585.0397
Schwarz criterion	605.8971	Hannan-Quinn criterion	593.3679
Autocorrel. coeff. (rho1)	−0.102156	Durbin h-statistic	−1.085335

Source: Own calculations using the GRETL package.

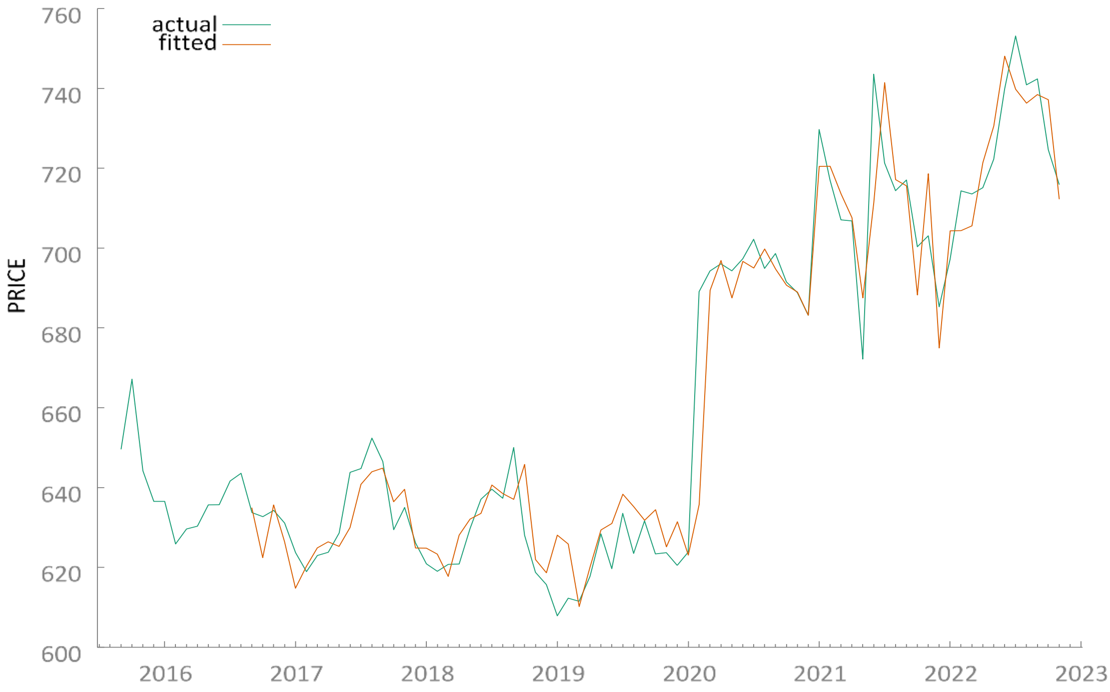

Figure 6. Actual and fitted values of variable: PRICE.

Source: Own calculations using the GRETL package and Table 2.

During the period under consideration, an increasing trend in the unit price occurred. An average monthly increase of nearly PLN 28/100 in the price per 1 MWh followed. What is more, a positive autoregression of the unit price has occurred. The current unit price results in more than 84% of the previous month's price. Additionally, autoregressive adjustments of the variable PRICE emerge, i.e., positive adjustment by more than PLN 35/100 every 11 months and negative by more than PLN 29/100 every 12 months. The empirical equation given in Table 3 describes the volatility mechanism of electricity unit price with great accuracy. More than 94% of the unit price volatility is explained. Figure 6 illustrates the price volatility, showing the actual and theoretical magnitudes of the variable PRICE.

5. Conclusions

Electrical energy is in this day and age fundamental to the functioning of every household. The use of gas, heating oil or solid fuels in home heating systems also involves the powering thereof with electrical energy. Today, electricity is the most environmentally friendly energy source. As experience has shown, the substitution of an oil-fired heating system with a heat pump resulted in significant financial savings for the household. What is more, the living comfort has improved due to the elimination of the need to purchase heating oil twice a year at minimum.

The econometric model of household electricity consumption presented in this paper confirms both the hypothesis about the feedback between the variables USAGE and PRICE as well as the recursive effect of the amount of electricity consumption on its value in monetary units. In addition to the cognitive value of the econometric modeling results obtained, the empirical tool constructed enables forecast estimation of energy consumption volume, its value and unit price in subsequent months, for at least 12 consecutive months. One significant unknown arises, however. Due to the energy crisis, it is difficult to determine - even in the short term - what the unit price for electricity supplied from the external environment will be. Yet, even with this unknown, a relatively accurate prediction of the future size of the variable USAGE is possible.

The analysis shows that the next investment in household should be a photovoltaic installation. It will bring great benefits in terms of greenhouses' gas reduction. It will also dramatically reduce current electric energy expenditures. An increase in the consumption of electricity in the household is observed after installing the heat pump. In addition, there is a negative feedback between the consumption of electricity in the household and its unit price.

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