Energy 196 (2020) 117175

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Seasonal variability of price elasticity of demand of households using zonal tariffs and its impact on hourly load of the power system

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A R T I C L E   I N F O

Article history:
Received 8 August 2019
Received in revised form
7 February 2020
Accepted 15 February 2020
Available online 19 February 2020

Keywords:
Price elasticity of demand
Cross elasticity
Self elasticity
Time-of-use tariffs
Demand response
Power system safety

A B S T R A C T

Price elasticity of electricity demand values are crucial for a proper design or retrofit of time-of-use electricity tariffs. The aim of this paper was to propose an alternative methodology for determination of self and cross price elasticity of demand with daily resolution for electricity customers changing their settlement to the time-of-use tariff. Progressing implementation of smart metering systems provides access to more accurate data reflecting the consumers' electricity consumption with at least hourly resolution, which has been a motivation to use load profiles data to analyze customer's price elasticity. The method is based on load profiles' comparison of customers using flat and time-of-use tariffs. A case-study example is presented for residential consumers settled according to time-of-use tariff in the area of one of Polish distribution system operators and the resulting price elasticity values vary significantly over the year. Effectiveness of zonal tariffs is also evaluated, along with their impact on the power system's load in the summer and winter peak load periods. The results may be used by supply companies and distribution system operators to improve efficiency of applied demand response programs based on time-of-use tariffs and thus influence the safety of the power system operation.

1. Introduction

Demand side response is becoming an increasingly important area of influence on the effective and safe operation of the power system mainly resulting from the rising share of renewable energy in covering the load, at the expense of large system power plants traditionally used to control the operation of the power system.

Demand side response programs are divided into two classes: price- and incentive-based [1]. Both groups of demand management programs create conditions for remunerating the consumers for reducing the loads in the periods of peak load of the power system. Tariffs systems are widely used around the world for electricity demand management purposes. The significant impact of most popular tariff programs like time-of-use (TOU) tariffs is based on the long-term response of consumers to price signals although it does not allow real-time control of the electricity consumption except tariffs with a critical-price pricing (CPP) or real-time pricing (RTP) [2,3]. This paper focuses on the price-based programs, specifically on the time-of-use tariff systems for residential customers, which create a stable system of continuous customers' response to the price differentiation for electricity utilization at particular hours of the day. Zonal tariffs are the most common and the only demand side response program available to households in Poland, used only by more than 20% of residential customers [4] so the knowledge of their behavior on the market is particularly important as they represent a significant potential for future implementation of load management programs.

Benefits from introducing zonal tariffs stem from the customers' price elasticity of demand and its use to induce sales growth and change the energy consumption profiles, so as to reduce peak period energy sales and increase the consumption during off-peak periods [5–8]. That is why the proper design of zonal tariffs requires knowledge of the price elasticity of electricity demand, which determines the behavior of consumers in individual price zones. Price elasticity of demand was already used in the second half of the 20th century to forecast the demand for electricity [9] or to analyze the reduction in peak demand when using zonal tariffs [10]. In Ref. [11] it was noticed that the values of price elasticity of demand are variable over time. In summer, the absolute values of price elasticity of demand were much higher than in winter [11], probably dependent on the seasonal electricity consumption level.

The price elasticity of demand, defining the behavior pattern of

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https://doi.org/10.1016/j.energy.2020.117175

electricity consumers, is widely used to design tariff programs, and in particular TOU tariffs [12–14]. Numerous studies focus on determining merely the self elasticity, based on data on electricity consumption and prices in subsequent years and referring them to each other. In Ref. [15] an analysis of data from 36 studies on elasticity carried out in the years 1947–1997 is presented, where the short-term average elasticity value is −0.35, while in Ref. [16] analysis of data from over 400 studies regarding elasticity in the years 1997–2011 is described, and the average elasticity value determined equals −0.13. In Refs. [17–19], the values of self elasticity of electricity demand for the residential consumers range from −0.30 for the short-term elasticity to −2.417 for the long-term one. Absolute values of the long-term elasticity are higher, because the consumer may react to the price increase by exchanging the equipment used for more energy-efficient, but at the same time they are more difficult to determine, because they require analysis of a larger amount of data [20].

Apart from self elasticity, it is also important to consider the cross elasticity of demand. Studies of the cross price elasticity of electricity demand take different assumptions regarding electricity substitutes. The standard approach assumes that other energy carriers are substitutes for electricity, which is why the cross elasticity is determined for natural gas, oil or wood [21–24]. In Refs. [20,25] it is assumed, however, that electricity demand levels in the peak and off-peak periods of the zonal tariff are substitutes and the cross elasticity is determined for particular tariff zones.

In order to use the price elasticity of demand for the design of effective demand control programs, it seems necessary to consider the price elasticity of demand as a variable value over time and depending on many factors. Price elasticity may vary for particular hours of a day, days of the week or seasons [26,27] and may also depend on climatic or housing conditions [28,29]. In Refs. [30,31] it is suggested to use the Kalman filter to underline the volatility of price elasticity due to economic activity or price level and regulation. In some of the studies and models analyzed, it is assumed however that the price elasticity of demand is a constant feature of a given customer in the analyzed time period [32,33].

This paper presents a new, original method of determining self and cross price elasticity of demand based on customers' load profile analysis. The widespread use of smart meters provides a new base of load profiles for such analysis and enables future prediction of load profiles in the following days for zonal tariff programs [34]. The research presented in this article concerns residential customers, who serve as an example to apply the proposed method of price elasticity determination, similarly to Refs. [24,28,35]. Case-study analysis is presented for a sample group of residential consumers supplied within the area of one of Polish Distribution System Operators (DSOs). This original method is then used to calculate the influence of the customers' consumption profile change on the power system's load, as a consequence of zonal tariffs' use, which is crucial to evaluate possible threats concerning the power system generation adequacy and safe operation especially at the system peak load hours.

The main contributions of this paper are: a) proposal of a novel method of determining self and cross price elasticity of electricity demand on the basis of comparison of load profiles of customers using zonal tariff in relation to flat tariff, b) determination of the original self and cross elasticity values with the resolution of one day for the period of one year for households in a selected distribution area in Poland, for the purposes of presenting the proposed method, c) original assessment indicators of the effectiveness of the TOU tariffs for households and the original method for estimating the influence of TOU tariffs' use on the whole power system in individual hours of the day based on the analyzed load profiles change. The determined price elasticity of demand values apply to residential customers using the zonal tariff, not to all households.

The article is organized as follows: section 1 describes the importance of the demand side response programs using zonal tariff, the literature review as well as the motivation and the main contributions of the paper, while section 2 introduces the method of determining the price elasticity of demand of customers using zonal tariffs. Section 3 presents the results of the case-study for determining self and cross price elasticity of demand for a sample power distribution area, discusses the validation of the obtained results and assesses the effectiveness of the two-zone tariff for households in the considered area, as well as and the influence of the considered group of residential customers using TOU tariffs on the power system load in individual hours of the day. Finally, a conclusion of the research is presented in section 4.

2. Methodology and data applied for demand price elasticity determination of customers using zonal tariffs

The alternative method of determining price elasticity of demand, presented by the authors below, encompasses numerous calculation steps. Firstly, appropriate definitions of demand price elasticity for the customers settled according to TOU tariff need to be recalled, then the methodology of their calculation is presented. The methodology contains the following principal steps leading to price elasticity of demand determination:

- formulating the relationship between the changes in electricity consumption under the considered flat and TOU zonal tariffs, the price changes within these tariffs as well as self and cross price elasticity of demand values - equations (8) and (9),
- establishing the relationship binding the annual energy consumption levels of a representative customer of TOU and flat tariffs following the analysis of standard load profiles of these tariff groups – equation (13),
- determining daily electricity consumption changes in peak and off-peak zones of the TOU tariff comparing to the consumption registered for the flat tariff based on standard load profiles reflecting the annual consumption of the representative customers of the flat and the TOU tariff groups,
- calculations of daily self and cross elasticity values – equation (14)–(16).

The steps enumerated above are presented in detail in the following subsections.

2.1. Definition of demand price elasticity of customers using zonal tariffs

In this paper, authors describe the price elasticity of demand of zonal tariff customers using equations (1)–(3), presenting changes in energy consumption ΔE from the initial value E_1, for the flat tariff, to the resultant E_2 value in case of electricity consumption settled according to the zonal tariff, being the result of change in the energy settlement price ΔP from the initial P_1 value to the price P_{2av} defined by equation (4), for the zonal tariff inducing a change in the electricity consumption [36]:

$$\Delta E = E_2 - E_1 \tag{1}$$

$$\Delta P = P_{2av} - P_1 \tag{2}$$

$$\varepsilon = \frac{\Delta E}{E_1} \bigg/ \frac{\Delta P}{P_1} \tag{3}$$

The elasticity value is a result of averaging the benefits of reducing consumption in peak periods, increasing the consumption in off-peak periods and shifting consumption from peak to off-peak periods. This way of assessing the benefits of introducing zonal tariffs is useful for final electricity consumers, for whom it is important to cover electricity demand at low costs.

For the organizers of demand control programs, such as suppliers, who want to avoid excessive energy purchases in peak periods or network operators responsible for ensuring power balance in the system or for reducing overloads in network system components during peak load periods, it is particularly interesting to shift energy usage from the peak period to the off-peak period. Authors of the paper would like to stress that it is a very desirable feature of the zonal tariff, which is ignored in the concept of change in energy consumption ΔE in equation (1). The average demand change does not allow to assess the current benefits resulting from the load profile change in daily periods, as a result of electricity consumption shift from the peak period to the off-peak period which may result in zero energy balance. The zonal consumption change influence however the change of the final settlement price P_{2av}, being the average value of zonal prices P_i for the tariff containing n zones weighted by energy consumption in these zones E_i given by equation (4):

$$P_{2av} = \frac{\sum_{i=1}^{n}(E_i \cdot P_i)}{\sum_{i=1}^{n} E_i} \tag{4}$$

Equations (2)–(4) use the concept of electricity billing price P for a flat or zonal tariff, which include all costs incurred by customers, excluding taxes, related to purchase of electricity and its distribution. Equation (5) presents the method to determine the total electricity price in both flat and TOU tariffs in Poland:

$$P = C_E + S_V + S_Q + \frac{\sum OCi}{E_a} \tag{5}$$

where: C_E – unit electricity price in flat tariff or in particular zones of TOU tariff; S_V – variable rate of the distribution fee in flat tariff or in particular zones of TOU tariff; S_Q – variable quality rate uniform for all residential tariffs; ΣO_{Ci} – sum of fixed distribution fees in flat or TOU tariffs; E_a – annual electricity consumption of the considered consumer.

For the purposes of further analysis, changes in energy consumption of the consumer shifting the settlement from flat to TOU tariff need to be considered. Electricity consumption change in zonal tariff may be influenced by two phenomena. Firstly, a lower price may cause an increase in energy consumption in the time zones in which it applies or decrease the consumption in high-price zones. Reactions of the customer changing their electricity settlement from flat to two-zone tariff, i.e. a change in electricity consumption E_i in the ith zone in relation to energy consumption in the same time interval in flat settlement E_{1i}, as a result of a change in the settlement price ΔP_i in the ith zone in relation to the flat settlement price P_{1i}, may be described with self price elasticity of demand ε_s [36] defined with equation (6):

$$\varepsilon_s = \frac{\Delta E_i}{E_{1i}} \bigg/ \frac{\Delta P_i}{P_{1i}} \tag{6}$$

Such a reaction for price change should be used by organizers of demand control programs to increase energy sales for specific purposes in specific time zones or to limit the sales in other zones. The self elasticity values are usually negative and the higher their absolute values are, the more effectively the demand management is performed using the change in electricity price and its distribution fees.

The second mechanism of the customer's reaction to price changes is the possibility of shifting the energy consumption of ΔE_i to the ith zone, in relation to the initial energy consumption E_{1i} in this zone in the flat settlement, from the jth zone with changed energy billing prices by ΔP_j in relation to flat tariff's price P_{1j}. The relative value of energy shifted to the ith zone in relation to the relative price difference that occurred in the jth zone may be described with cross price elasticity of demand ε_c and expressed with equation (7) [36]:

$$\varepsilon_c = \frac{\Delta E_i}{E_{1i}} \bigg/ \frac{\Delta P_j}{P_{1j}} \tag{7}$$

Cross elasticity values are usually positive, because the increase in price of one product increases the demand for its substitute, which is the use of electricity in another zone with lower costs. Such reaction to price change should be used by organizers of demand control programs in order to efficiently shift energy sales from one zone to another to reach the desired effects. However, if the consumption increase is observed not only in low-price zones but also in high-price zones despite the increased prices there, demand levels in both zones are complementary and thus negative values of cross elasticity may be expected.

Elasticity values described in the following calculations are based on consumers' hourly electricity consumption levels that may be obtained using smart metering systems. In the absence of such systems in many areas in Poland, standard load profiles for individual tariff groups published by distribution system operators may be used. They concern customers with a contracted capacity of less than or equal to 40 kW, not equipped with smart metering system and they are used to enable hourly settlement of energy sellers, supplying these low voltage small customers with electricity, on the wholesale market. The profiles represent relative hourly consumption data for the period of year for a representative customer of a considered tariff and are based on customers' load profile measurements performed by DSOs for a sample group of 500 consumers. The profiles for tariffs commonly used for households in Poland, a flat G11 and two-zone TOU G12 tariffs, are presented for selected dates in Fig. 1, based on data published by one of Polish DSOs. Settlement prices for those tariffs are depicted in Fig. 1 as well and presented in detail in Table 1. To simplify the observation of variability of load profiles and tariff prices, data presented with the resolution of 1 h in Fig. 1 is connected with continuous lines for load profiles or with dotted lines for prices. Load profiles are presented for one day in the heating season (January 9) and one day in the non-heating season (August 9) for 2017 to show the profiles' variability. Similar variability of consumption levels and prices was observed for 2016, thus they are not illustrated in a separate chart.

In order to calculate the values of self and cross elasticity of electricity consumers using zonal tariffs, a model of multi-zone elastic load [25,32], which determines hourly consumption profile changes in result of changes in hourly prices and the hourly values of self and cross price elasticity of demand, may be used. When analyzing a flat and a two-zone tariff and if the hourly consumer's electricity consumption values both in flat and TOU tariff are available, electricity consumption in peak zone p and off-peak zone o for both tariffs may be obtained by adding hourly loads for hours forming particular zones. In case of changing the settlement from flat to TOU tariff, containing the peak and off-peak zone, changes in electricity consumption in the peak zone ΔE_{G12ph} and in the off-peak zone ΔE_{G12oh} can be expressed in the function of zonal consumption values in the analyzed TOU tariff's zones and respective periods in the flat tariff E_{G11ph} and E_{G11oh}, the changes in settlement prices in the peak P_{G12p} and off-peak P_{G12o} zones in relation to the flat rate P_{G11} and the self and cross price elasticity of demand ε_s and

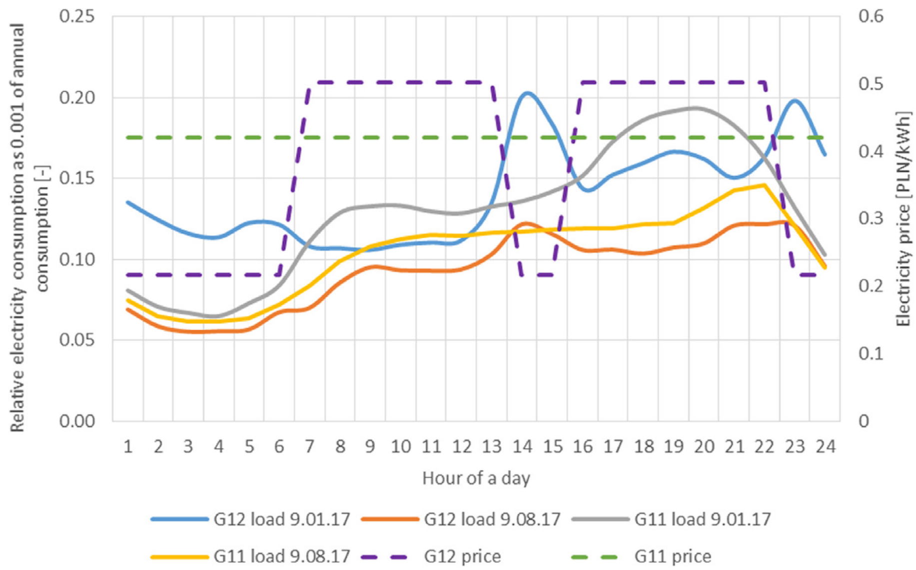

Fig. 1. Daily variability of standard load profiles of the G11 and G12 tariff consumers for chosen days of the heating and non-heating period for the considered DSO [37] and tariff variable components of prices and distribution fees for 2017.

Table 1
Energy prices and distribution fees for flat tariff G11 and TOU tariff G12 of electricity supplier Enea S.A. and DSO Enea Operator Sp. z o.o.

Tariff		Energy prices		Variable distribution fee		Quality fee	Fixed distribution fee	Total electricity variable fee	
		PLN/kWh		PLN/kWh		PLN/kWh	PLN/month	PLN/kWh	
		peak	off-peak	peak	off-peak	24 h		peak	off-peak
2016	G11	0.2545		0.1621		0.0129	9.95	0.4295	
	G12	0.3188	0.1479	0.1823	0.0600	0.0129	12.16	0.5140	0.2208
2017	G11	0.2424		0.1610		0.0127	12.99	0.4161	
	G12	0.3036	0.1402	0.1823	0.0600	0.0127	15.20	0.4986	0.2129

ε_c. Equations describing these values, derived by authors based on the above-mentioned model [25,32] and on the assumption of constant values of self and cross elasticities ε_s, ε_c for each of 24 h analyzed [25] are defined as follows:

$$\Delta E_{G12p} = E_{G11p} \cdot \left(\varepsilon_s \frac{P_{G12p} - P_{G11}}{P_{G11}} + \varepsilon_c \frac{P_{G12o} - P_{G11}}{P_{G11}} \right) \tag{8}$$

$$\Delta E_{G12o} = E_{G11o} \cdot \left(\varepsilon_s \frac{P_{G12o} - P_{G11}}{P_{G11}} + \varepsilon_c \frac{P_{G12p} - P_{G11}}{P_{G11}} \right) \tag{9}$$

2.2. *Practical determination method of self and cross price elasticity of demand*

In order to determine self and cross price elasticity of demand by solving the system of equations (8) and (9), data concerning the consumption under G11 tariff E_{G11} divided into in peak E_{G11p} and off-peak E_{G11o} periods is necessary together with changes in electricity consumption in particular zones ΔE_{G12p} and ΔE_{G12o} being a result of a tariff change from G11 flat tariff to G12 TOU tariff. With the load profiles of the two groups of final customers, settled according to flat G11 tariff and zonal G12 tariff, the authors used equations (10) and (11) to determine the above-mentioned consumption values and their changes for a period containing h hours:

$$\Delta E_{G12p} = E_{G12p} - E_{G11p} = E_{aG12} \sum_{ph} H_{G12ph} - E_{aG11} \sum_{ph} H_{G11ph} \tag{10}$$

$$\Delta E_{G12o} = E_{G12o} - E_{G11o} = E_{aG12} \sum_{oh} H_{G12oh} - E_{aG11} \sum_{oh} H_{G11oh} \tag{11}$$

where: E_{G11p}, E_{G11o}, E_{G12p}, E_{G12o} — peak and off-peak consumption levels in particular tariffs for analyzed time period, H_{G11ph}, H_{G11oh}, H_{G12ph}, H_{G12oh} — relative hourly electricity consumption values in the hour h for the considered standard load profiles of G11 and G12 tariff for peak and off-peak zones, E_{aG11}, E_{aG12} — annual electricity consumption of the considered customers in G11 and G12 tariff.

To determine energy consumption in particular zones according to equations (10) and (11) on the basis of load profiles, the knowledge of annual electricity consumptions E_{aG11} when using the G11 tariff and E_{aG12} after transferring to G12 tariff is necessary. Based on the analysis of standard load profiles for the considered tariff groups, the authors of this paper devised a relationship between above-mentioned annual consumption values determined by equations (12) and (13) explained below.

The decision of the G11 tariff group consumer to move to the G12 tariff is the most often induced by the intention to use electricity also for space heating or reheating purposes [37,38]. Then, the usage of electricity in the off-peak zone is increased. Being settled in the zonal tariff, the customer may also wish to shift the use of household appliances to the period of off-peak prices to generate savings. Both of these factors occur simultaneously in the heating period, however in the non-heating period, savings are only possible as a result of shifting the household appliances load to the off-peak zone.

Fig. 2 presents the levels of daily electricity consumption of representative customers settled in G11 and G12 tariff broken down by peak or off-peak zone. The duration of the non-heating season has been marked by the points of intersection of the trend line for the reduction of energy use in the spring season and the increase in energy use in the autumn with a stable level of energy use during summer, which are determined based on G12 tariff off-peak energy consumption.

It is assumed that in the non-heating season the G12 consumer does not use electricity for space heating purposes. In such case, in the non-heating period, the reduction of electricity consumption in the peak zone of G12 consumers in relation to consumption of G11 customers is offset by the increase in G12 customers' consumption in relation to G11 consumers in the off-peak zone - this phenomenon is caused by shifting the use of household appliances by G12 tariff customers to the off-peak zone and occurs evenly to a similar degree on all days of the year. It is assumed that both tariffs' electricity users are of similar size concerning the energy consumption of appliances utilized.

Having hourly relative consumption values for standard load profiles of tariff groups G11 and G12, the transfer of loads to the off-peak G12 zone, reflecting differences in energy consumption in the non-heating period in the tariffs G11 and G12, can be described by equation (12):

$$\begin{aligned} &E_{aG11}\sum_{L_s}^{L_e}\sum_{p}H_{G11i} - E_{aG12}\sum_{L_s}^{L_e}\sum_{p}H_{G12i} \\ &= E_{aG12}\sum_{L_s}^{L_e}\sum_{o}H_{G12i} - E_{aG11}\sum_{L_s}^{L_e}\sum_{o}H_{G11i} \end{aligned} \tag{12}$$

where: L_s, L_e − beginning and end of the non-heating period, p − hours of the peak period, o − hours of the off-peak period.

Based on (12) the annual electricity consumption of the representative consumer of the G11 tariff group before deciding to transfer to G12 tariff may be determined as follows (13):

$$E_{aG11} = E_{aG12}\frac{\left(\sum_{L_s}^{L_e}\sum_{o}H_{G12i} + \sum_{L_s}^{L_e}\sum_{p}H_{G12i}\right)}{\left(\sum_{L_s}^{L_e}\sum_{o}H_{G11i} + \sum_{L_s}^{L_e}\sum_{p}H_{G11i}\right)} \tag{13}$$

Equation (13), elaborated by the authors based on load profiles' analysis, allows to determine the mutual relation of annual energy consumption of the representative customer for the considered tariff groups, with the analyzed load profiles published by the DSO when changing the tariff settlement from flat to TOU tariff. In particular, the annual equivalent energy consumption of G11 customers, before changing the settlement to G12, having a certain level of annual consumption in the G12 tariff, may be determined based on this equation, which reflects changes in the manner and purposes of electricity use of these customer groups settled according to a given tariff within the area of particular DSO and characterized by standard load profiles.

The values of self and cross elasticity of demand can be obtained using equations (14) and (15), with the assumed values of E_{aG12} and E_{aG11} related by equation (13) and calculating all necessary consumption values for the analyzed period using (10) and (11):

$$\begin{aligned} \varepsilon_S = &\left[E_{G11p}\cdot \Delta E_{G12o}\cdot (P_{G12o} - P_{G11}) - E_{G11o}\cdot \Delta E_{G12p}\right. \\ &\left.\cdot (P_{G12p} - P_{G11})\right]\cdot\beta \end{aligned} \tag{14}$$

$$\begin{aligned} \varepsilon_C = &\left[E_{G11p}\cdot \Delta E_{G12o}\cdot (P_{G12p} - P_{G11}) - E_{G11o}\cdot \Delta E_{G12p}\right. \\ &\left.\cdot (P_{G12o} - P_{G11})\right]\cdot(-\beta) \end{aligned} \tag{15}$$

$$\beta = \frac{P_{G11}}{E_{G11p}\cdot E_{G11o}\cdot\left[(P_{G12o} - P_{G11})^2 - \left(P_{G12p} - P_{G11}\right)^2\right]} \tag{16}$$

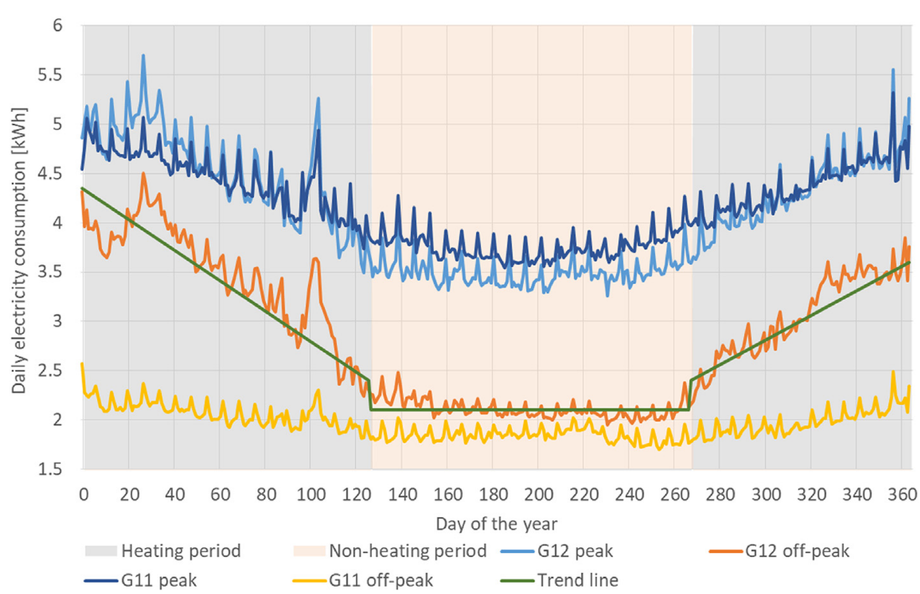

Fig. 2. Daily electricity consumption levels of the consumer settled according to the G12 tariff, with an annual consumption of 2526 kWh, broken down into consumption in the peak and off-peak periods and of the consumer settled according to the G11 tariff, with annual consumption of 2236 kWh, divided into energy consumed in specific time zones of the G12 tariff, according to the standard load profiles of the Enea Operator DSO for 2017.

3. Calculation results for the case study and their discussion

Presented methodology has been applied to calculate self and cross demand price elasticity values for electricity supply of residential consumers in the chosen distribution area in Poland. The obtained results are discussed taking into consideration the accuracy of calculated values, their possible applications, the efficiency of the considered time-of-use tariff operation and the impact of the TOU tariff's customers on the hourly load of the country's power system.

3.1. Price elasticity of demand calculation results

The chosen group of customers using two-zone TOU tariff for the case study calculations of self and cross price elasticity of demand constitute over 20% of more than 2 000 000 residential customers situated in north-western Poland settled for electricity by energy supplier Enea S.A. and distribution system operator Enea Operator Sp. z o.o. in accordance with electricity tariffs approved by the regulatory authority. The calculations were conducted for two data sets concerning the tariffs G11 (flat) and G12 (TOU) based on standard load profiles [39,40] and average energy consumption levels of G12 tariff representative customers [41] for the years 2016 and 2017 to ensure comparative analysis of the results. Electricity prices and distribution fees for the considered time periods and area are presented in Table 1, while the considered annual electricity consumption levels are presented in Table 2. For both years, the duration of the non-heating season is based on standard load profiles and equals 141 days. The peak periods in the TOU tariff analyzed are 6 a.m. to 1 p.m. and 3 p.m.–10 p.m. on each day of the week, while the remaining hours constitute the off-peak period.

The calculated daily self and cross price elasticity of demand values of the G12 tariff customers for the analyzed DSO using equations (14) and (15) are presented for 2016 and 2017 in Fig. 3.

Table 2
Annual average electricity consumption levels of residential consumers.

Year	2016		2017	
Tariff	G11	G12	G11	G12
Annual electricity consumption [kWh/a]	2389[a]	2687	2236[a]	2526

[a] Values calculated using equation (13).

Analysis of the chart in Fig. 3 allows to formulate the following conclusions:

- the exemplary calculation of the price elasticity of demand of customers using zonal tariffs in the analyzed distribution area shows a high variability of both the self and cross elasticity values of such customers; daily values of self and cross elasticity with fixed tariff prices vary daily depending on changes in the seasonal use of electricity; during heating season, the energy needs of customers force decreasing elasticity values, while in the non-heating season the values of elasticity are stabilized;
- the daily self elasticity values of zonal tariff's customers are negative as expected and change within the range from −0.1 to −3.0; lower absolute elasticity values are characteristic of the summer season, while higher absolute elasticity values occur in the winter season;
- cross elasticity values are positive in the summer season within the range from 0 to 0.2, as electricity is not used then for heating purposes and the users of TOU tariffs can shift the use of household appliances to the off-peak zone with the aim of making profit from the cheaper electricity in that zone as a substitute of the more expensive electricity during the peak zone; in the heating season, however, the properties of the cross elasticity change as its values become negative, with small absolute values for the beginning of autumn and at the end of spring and reach −1.5 for the winter season; the negative values of cross elasticity are due to the use of available electric heating devices at peak zones during periods of cold days, which use should rather be expected off-peak; electricity use for space heating purposes observed during heating season in peak zone as well, depends on outside weather conditions and becomes a complementary product to the electricity used for space heating off-peak, which is observed by negative values of cross elasticity.

With the daily self and cross elasticity values, ε_s and ε_c respectively, the profile of electricity consumption can be determined with the hourly resolution for the new or modified G12 m tariff, in terms of prices and periods of their validity, starting from the

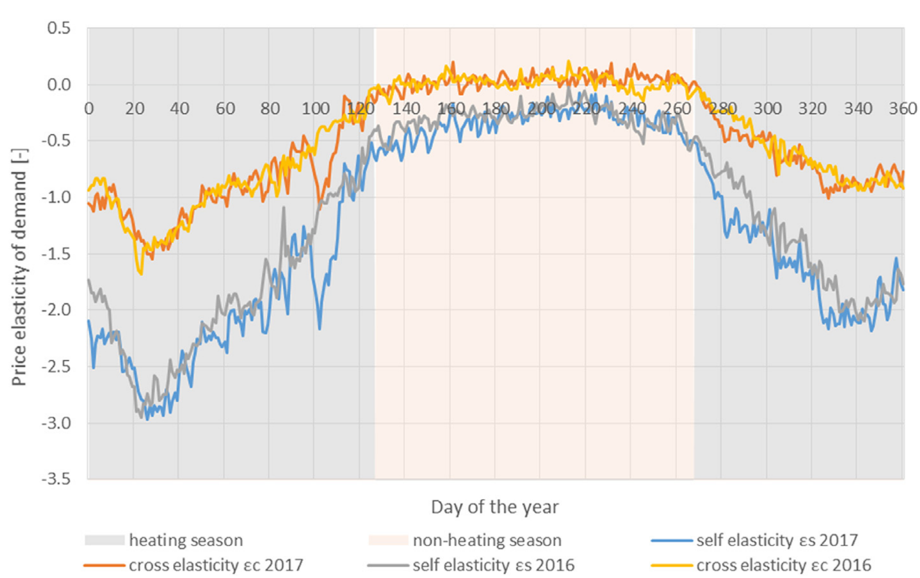

Fig. 3. Daily variability of self and cross price elasticity of demand level for G12 tariff customers for standard load profiles of G11 and G12 tariff group for the considered DSO in 2016 and 2017, based on the average annual consumption levels (Table 2).

hourly flat tariff consumption available with 1-h resolution and modified prices applicable at peak and off-peak hours based on equations (8) and (9). It is possible if assuming that the self and cross elasticity values remain constant when prices and periods of their application change. This assumption seems appropriate for minor price and consumption changes compared to the original zonal tariff for which the elasticities were determined, although generally the price elasticity of demand is non-linear, which is emphasized in Ref. [42].

The obtained results concerning the daily self and cross price elasticities of demand should be verified in the contexts of accuracy and the ability to forecast the future customer load profiles in consequence of zonal price changes, which could enable estimation of their usefulness in real-life practice for the tariff design and modification. The authors' idea to perform such verification is the reconstruction of the G12 tariff's profile based on G11 profile and the calculated elasticity values. Such load profile mapping should be followed by the errors estimation by comparing the calculated load profile with the original standard profile published by the DSO. The attempt to recreate the hourly load profile of the G12 tariff associated with accuracy determination of hourly mapping errors have been performed starting from hourly values of G11 and determined self and cross elasticity values and energy consumption increases given by (8) and (9). The results for the year 2017 in the form of a reproduced G12r load profile are shown in Fig. 4 for $E_{aG12} = 2.526$ MWh/a and for the day with the largest hourly mapping error within the year in relation to the value of the standard load profile. The mapping error for particular hours h is calculated as the difference between the original and reproduced electricity consumption level $\Delta G12r_h = G12_h - G12r_h$.

The sum of the mapping errors of G12r profiles in relation to G12 for 24-h period equals zero, but the maximum hourly error for 3 p.m. on 11 February 2017 reaches 25.6% of the actual value of the G12 profile. The average percentage value of the hourly mapping error to the hourly value of the G12 profile for all mapped hours in the year 2017 is 5.53%. The similar error values were found when analyzing the results for the year 2016 for which the maximum hourly error was found at the same hour 3 p.m. but on 30 January 2016 and reached 29.3% of the actual value of the G12 profile with the average value of such errors for the whole year being 5.64%.

3.2. Assessment of G12 tariff efficiency

The already performed calculations of price elasticities of demand allow to analyze the impact of the transition of customers currently using G12 TOU settlement, from the flat settlement G11, in terms of the efficiency of the G12 tariff actually offered. The increments and reductions of daily energy consumption in analyzed zones are the consequence of lowering (or increasing) the price in a given zone and transferring energy consumption between zones in accordance with economic, climatic or social impacts.

Changes in the amount of electricity consumed in the peak ΔE_{G12ps} or in the off-peak zone ΔE_{G12os} of the TOU tariff, due to price change in this zones in relation to the flat tariff can be determined by summing the impacts for i hours of the peak zone or k hours of the off-peak zone resulting from the change in prices in these zones and the value of self elasticity of demand with equations (17) and (18).

$$\Delta E_{G12ps} = \sum_{h=1}^{i} E_{G11h} \bullet \varepsilon_s \bullet \frac{P_{G12p} - P_{G11}}{P_{G11}} \tag{17}$$

$$\Delta E_{G12os} = \sum_{h=1}^{k} E_{G11h} \bullet \varepsilon_s \bullet \frac{P_{G12o} - P_{G11}}{P_{G11}} \tag{18}$$

The expected values of ΔE_{G12ps} are negative for the higher price in the peak zone and the negative self elasticity value, while the expected values of ΔE_{G12os} are positive for the lower price in the off-peak zone and the negative self elasticity value.

Similar changes in electricity consumption in the zonal tariff in relation to the flat tariff can be determined as a result of the impact of price changes and demand cross price elasticity. Shifting part of the energy consumed in the flat tariff in peak hours to the off-peak zone of the zonal tariff ΔE_{G12oc} due to the increase in prices in the peak zone of the zonal tariff in relation to the flat tariff can be determined by (19).

$$\Delta E_{G12oc} = \sum_{h=1}^{k} E_{G11h} \bullet \varepsilon_c \bullet \frac{P_{G12p} - P_{G11}}{P_{G11}} \tag{19}$$

The expected values of ΔE_{G12oc} are positive for the higher price in the peak zone and the positive values of cross elasticity.

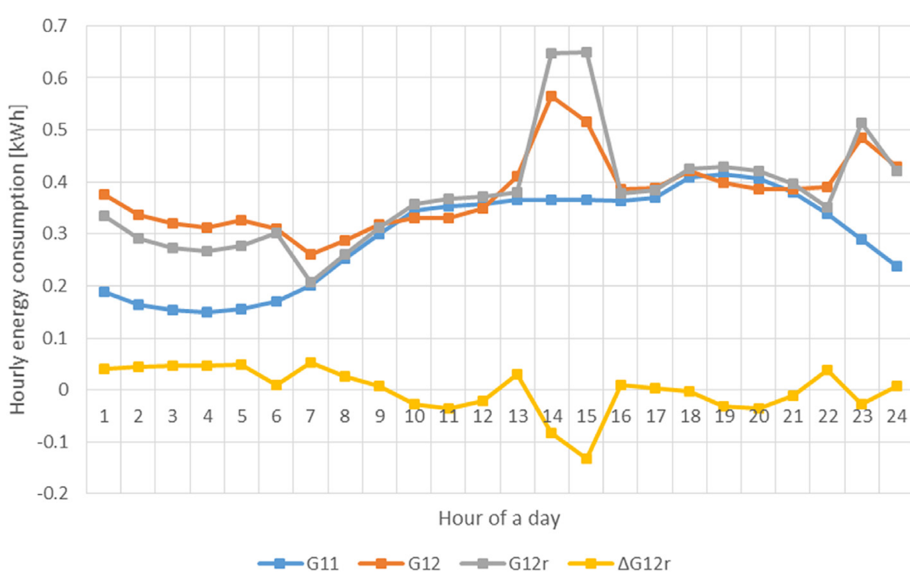

Fig. 4. Electricity consumption profile in accordance with the real G11 and G12 profiles as well as the reproduced profile G12r obtained using the determined elasticity values ε_s and ε_c together with the hourly mapping error ΔG12r for the day of 2017 with the largest hourly mapping error (Saturday, 11 February 2017).

Shifting part of the electricity consumed in the flat tariff in the off-peak hours to the peak zone of the TOU tariff ΔE_{G12pc} despite lowering prices in the off-peak zone of the TOU tariff in relation to the flat tariff, can be determined by (20):

$$\Delta E_{G12pc} = \sum_{h=1}^{i} E_{G11h} \cdot \varepsilon_c \cdot \frac{P_{G12o} - P_{G11}}{P_{G11}} \tag{20}$$

Expected ΔE_{G12pc} values are negative for the lower price in the off-peak zone and induce positive values of cross elasticity in case of substitute products. In case of severe climatic conditions the consumption in peak zone can increase despite lower price in the off-peak zone due to the possibility of using purchased equipment for heating purposes or in case of various social events. It becomes then a complementary product to the off-peak heating which is reflected by the negative values of cross elasticity.

The electricity consumption change in the peak or in the off-peak period can be determined by adding together the effects resulting from the self and cross elasticity for a given zone in accordance with the following equations:

$$\Delta E_{G12p} = \Delta E_{G12ps} + \Delta E_{G12pc} \tag{21}$$

$$\Delta E_{G12o} = \Delta E_{G12os} + \Delta E_{G12oc} \tag{22}$$

The effectiveness of the zonal tariffs' influence can be considered as the effectiveness of its impact in particular zones, determining the change in energy consumption in a given zone of the zonal tariff from the energy consumption in the corresponding period of flat tariff. The authors propose the following relationships describing the zonal efficiency indicators for the peak and off-peak zones:

$$EF_{p\%} = 100 \cdot \frac{\Delta E_{G12p}}{E_{G11p}} \tag{23}$$

$$EF_{o\%} = 100 \cdot \frac{\Delta E_{G12o}}{E_{G11o}} \tag{24}$$

Having devised the zonal efficiencies defined above the authors propose to define the average daily energy efficiency of the zonal tariff, using the following equation (25):

$$EF_{en\%} = 100 \cdot \frac{\Delta E_o - \Delta E_p}{E_{G11}} = EF_{o\%} \frac{E_{G11o}}{E_{G11}} - EF_{p\%} \frac{E_{G11p}}{E_{G11}} = 100 \cdot \frac{\Delta E_{G12s} + \Delta E_{G12c}}{E_{G11}} \tag{25}$$

where: $\Delta E_{G12c} = (\Delta E_{G12oc} - \Delta E_{G12pc})$ – consumption change in the TOU tariff induced by the cross elasticity, $\Delta E_{G12s} = (\Delta E_{G12os} - \Delta E_{G12ps})$ – consumption change in the TOU tariff induced by the self elasticity.

Such definition of the G12 tariff's energy efficiency allows to indicate possible profits due to the energy shifting from the peak zone to the off-peak zone, and not only from the simple balance of consumption changes in the peak and off-peak zones.

Changes in zonal efficiency indicators of zonal tariff during the year based on the summation of changes in energy consumption in particular zones within one day given by (23) and (24) are shown in Fig. 5 together with daily average values of G12 tariff efficiency for the year 2017 given by (25), which reflect the efficiency of changing the customer's load profile after changing the tariff settlement from G11 to G12.

The graphs presented in Fig. 5 allow to formulate the following conclusions:

- the efficiency of the zonal tariff is characterized by a strong seasonal impact, which is very important if the issues of power system safety are considered; reduction of energy consumption compared to the G11 tariff takes place only in the peak zone of the G12 tariff in summer; the largest increase in energy consumption occurs in the off-peak winter period as expected, but at the same time an increase in energy consumption of G12 customers during the peak period is observed, but it does not exceed 10% in relation to the flat tariff's consumption.
- the analyzed zonal tariff is only slightly effective in the peak period in the summer season, reducing by a few percentage points the load of customers using the zonal tariff in relation to the customers using the flat tariff; in the off-peak zone, the achieved efficiency is high with the level of 10% in summer to 80% in winter; the weighted average of the effects of limiting or

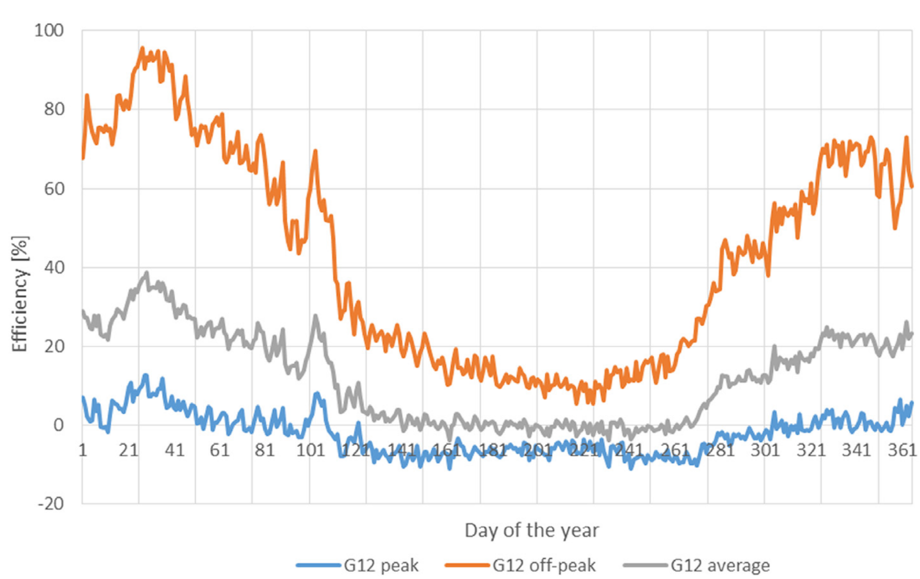

Fig. 5. Variability of G12 tariff zonal efficiency in the peak zone $EF_{p\%}$, in the off-peak zone $EF_{o\%}$ and the average efficiency $EF_{en\%}$ weighted by the electricity consumed in particular periods of G11 tariff for 2017.

increasing energy consumption in particular zones is at the almost zero level for the summer period and increases to 40% for the winter period.

3.3. Evaluation of G12 tariffs' impact on the load of the polish power system

The aim of this analysis is to demonstrate how residential electricity consumers may affect peak power system load changes through switching from the flat G11 tariff to the TOU G12 tariff and thus reducing or increasing the hourly peak load in the power system.

The positive results of the average zonal tariff efficiency do not guarantee that the hourly impact on peak system load is positive as well. To illustrate potential threats, the calculation results concerning the impact of the introduced two-zone tariff for the consumers' group supplied in the area of operation of one of the Polish DSOs exerted on the power systems' hourly load are presented. In the whole country, approximately 13.5 million customers were settled in the G11 tariff in 2017, with total demand of 23 910 GWh, and only about 2 million in the G12 tariff, whose demand amounted to 6721 GWh [41]. The analyzed DSO supplies more than 14% of residential customers settled according to the G11 or G12 tariff in Poland.

Data for the calculation of the customers' hourly influence on the power system's peak load due to tariff switching are based on the statistics concerning electricity consumption in the Polish power system [41,43] and are presented and explained in Table 3. The impact of the customers settled according to the G12 tariff is the sum of the impacts of individual customers which are represented by a group composed of L_{cG12} customers described as well in Table 3.

Simulations of the hourly impact of the G12 tariff consumers in comparison to consumption that would occur prior to the transition of these customers from the G11 to G12 tariff settlement is determined for individual hours in accordance with equation (26):

$$\varDelta E_{hG12-G11} = L_{cG12} \cdot \left(E_{hG12c} - E_{hG11c}\right) \tag{26}$$

where E_{hG12c} and E_{hG11c} are the hourly consumption levels of representative customers based on standard load profiles depicted in Fig. 2 for the analyzed hour.

Simulation calculations were performed using 2016 and 2017 data for the summer period from April 1 to September 30 for hours with a high probability of peak summer load, i.e. for hours from 10 a.m. to 6 p.m. [44] and for the winter period from January 1 to March 31 and from October 31 to December 31 for hours with high probability of peak winter load, i.e. for hours from 4 p.m. to 8 p.m. [44]. The results of calculations showing the ranges of TOU residential customers' impact for the most meaningful hours are presented in Figs. 6 and 7 for summer and winter seasons. As the results for the analyzed years are very similar, the charts present the results only for the year 2017.

According to equation (26), the positive values mean higher hourly consumptions for energy settlements according to the G12 tariff, i.e. an increase in hourly energy consumption as a result of changing the tariff settlement from G11 to G12. Negative values in the analyzed peak periods indicate a correct tendency, i.e. limitation of hourly consumption as a result of switching from flat to two-zone settlement.

Table 3
Data used to calculate the impact of the residential customers' tariff switching from G11 to G12 supplied in one of the Polish DSOs' area.

Data description	2016	2017
DSO's share in country's electricity consumption E_{aDSO} [GWh/a]	18 759	19 238
Share of residential consumption in the DSO S_{res} [p.u.]	0.259	0.225
Share of TOU in residential consumption S_{resZ} [p.u.]	0.221	0.219
Share of TOU in DSO's consumption $E_{aDSO\ resZ} = E_{aDSO} \cdot S_{res} \cdot S_{resZ}$ [GWh/a]	1038	948
Estimated average consumption of TOU customer E_{aG12} [MWh/a]	2.687	2.526
Estimated number of residential TOU customers $L_{cG12} = E_{aDSO\ resZ}/E_{aG12}$	386 304	375 297

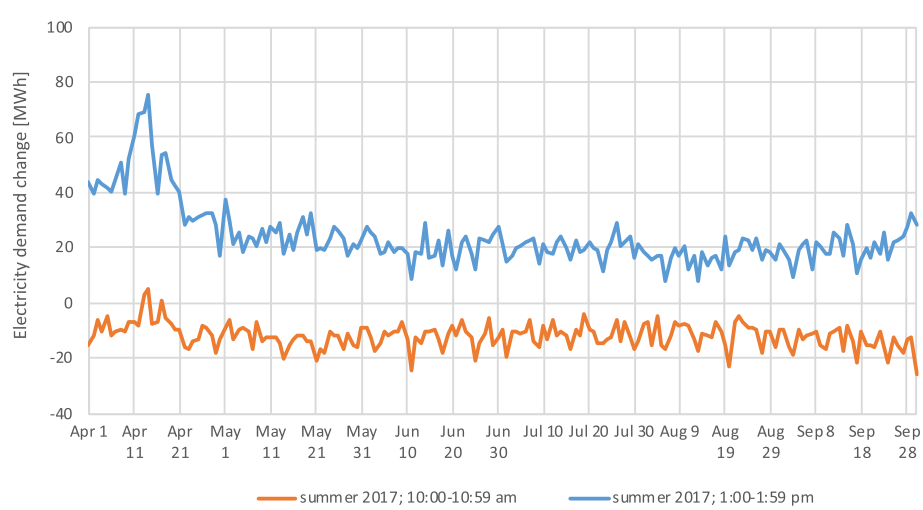

Fig. 6. Changes in energy consumption in two most meaningful hours in the peak period 10:00 a.m. - 2:00 p.m. of summer season 2017 for customers settled according to G12 tariff in relation to the consumption at G11 settlements for the area of the selected DSO.

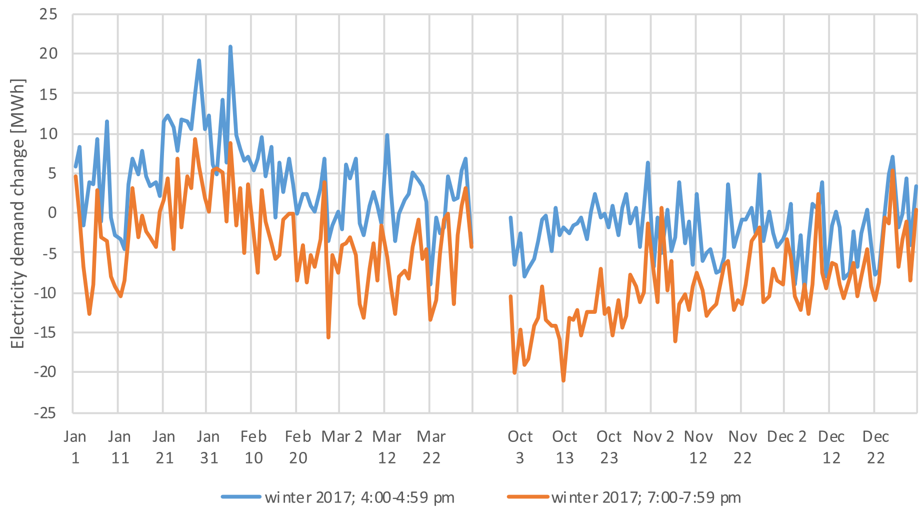

Fig. 7. Changes in energy consumption in two most meaningful hours in the peak period 4:00 p.m. - 8:00 p.m. of winter season 2017 for customers settled according to G12 tariff in relation to the consumption at G11 settlements for the area of the selected DSO.

Analysis of the presented changes in electricity consumption allows to formulate the following conclusions:

– the presented profiles are characterized by weekly variability with higher electricity consumption during holiday periods and lower consumption in the summer season; differences between consumption on business and holiday days reach 10 MWh;
– conducted simulations show an unfavorable impact of the zonal tariff load on the electricity system in April; the reason for that is an off-peak price zone from 1:00 p.m. 2:59 p.m. during the period of peak load of the system, which results in a load increase of the group of zonal tariff customers to almost 80 MW during cold spring days compared to their power consumption when using the flat tariff; in the summer season months, the increased impact of zonal tariffs' customers from 1:00 p.m. to 2:59 p.m. stabilizes at 20 MW; taking into account other DSOs impact, it can be estimated that the real negative impact of the G12 tariff in the peak summer load exerted by all Polish DSOs offering similar TOU residential tariffs is several times higher than 20 MW for the analyzed DSO;
– impact of zonal tariff customers on the peak load of the power system in winter, which occurs in Poland from 4:00 p.m. to 8:00 p.m., depends on the month and increases the peak load to 20 MW for the period 4:00–4:59 p.m. on very cold winter days and up to 10 MW during the warmer days of early spring; for later periods of the day, around 8:00 p.m., the hourly load in winter compared to consumption at a flat tariff is around -10 MW, except cold days where the load increases to $+10$ MW;
– in the autumn and early winter season, the load of zonal tariffs' customers is lower than the flat tariff's customers load by 5 MW for 4:00 p.m. and grows from -20 MW to -5 MW after 7:00 p.m. by the end of the year; positive values within a few MW range occur more often for 4:00–4:59 p.m. probably in the period of particularly cold days.

4. Conclusions

The authors presented the novel methodology concerning the determination of price elasticity of demand of customers using zonal tariffs. This new methodology can be distinguished comparing to the currently used methods by the following features:

– no need to analyze historical data for the past, subsequent time periods in many cases distorted by electricity market introduction or restructuring of supply companies and DSOs,
– the proposed elasticity determination method is basing on current customers' reaction to the market condition being offered and not previous ones existing in the past,
– making use of data provided by smart metering systems gradually implemented in EU as a result of European legislation advancement concerning energy sector and enabling to construct the load profiles of various groups of TOU tariff users,
– possibility to determine the daily values of self and cross price elasticity of demand,
– possibility to model the customer load change in result of changes of zonal prices and their duration within the day based on self and cross price elasticity of demand values, which was not possible without the knowledge of daily elasticity values,
– introduction of the new definition of zonal tariffs' efficiency and demonstration of its changes during the year,
– calculation of TOU customers group's influence on the hourly load of the power system.

The presented methodology for determining the elasticity of zonal tariffs for households was illustrated using the case of residential demand control for one of DSOs operating in Poland and enabled determining the TOU G12 tariffs' effects exerted by this group on the power system's load. The presented case-study analysis implies the following conclusions:

– household load profiles, obtained from smart metering systems for customers using the flat tariff and zonal tariff or based on the standard load profiles created on the basis of measurements carried out by the DSO, allow for determining the daily values of self and cross price elasticity of demand of electricity customers using zonal tariffs; the obtained daily self and cross elasticity vary from the small values in summer to significant absolute levels during winter and are influenced by the changes of seasonal customers' electricity consumption;
– the obtained values of self and cross price elasticity of demand can be used to model changes of customer load profiles in the case of minor modifications of zonal tariffs in terms of zonal prices and periods of their application (zones) with a maximum error of less than 30%, and a medium error of 6%, which may be

interesting for organizers of demand response programs through tariff interactions;

- in general, the transition of customers from the G11 tariff to G12 is favorable for summer, except for the hours from 1:00 p.m. to 2:59 p.m. when the off-peak zone of the G12 tariff applies; during winter, the benefits of limited energy consumption by customers settled according to G12 tariff seem to depend on the outside temperature, as load increases are observed, probably due to space heating at low temperatures; in the autumn-winter period, the energy consumption of the G12 tariffs is reduced in relation to G11;
- difficult situation in terms of energy balancing in summer periods should lead to the introduction of modifications to the G12 tariff within this season.

Prospects for a wider practical application of the presented methodology for determining the self and cross price elasticity of electricity demand of the customers using zonal tariffs and designing and modification of zonal tariffs on this basis will grow as smart metering systems develop, allowing the use of customers' real load profiles.

The price elasticity of demand determined by the presented methodology stems from the current observations of market reactions of consumers for the electricity price, therefore it is important for the real-time design and retrofitting of the TOU tariffs to reach the desired impact on customers and the power system.

CRediT authorship contribution statement

Jerzy Andruszkiewicz: Conceptualization, Methodology, Writing - review & editing, Project administration. **Józef Lorenc:** Validation, Supervision, Funding acquisition. **Agnieszka Weychan:** Conceptualization, Formal analysis, Investigation, Writing - original draft.

Acknowledgements

This work was supported by the study ordered by Polish Transmission System Operator PSE S.A. and the Institute of Electric Power Engineering of Poznan University of Technology grant no. 04/41/DSPB/4337.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2020.117175.

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