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Swiss residential demand for electricity by time-of-use

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Abstract

In this study, we have examined the residential demand for electricity by time-of-day in Switzerland. For this purpose, a model of two log-linear stochastic equations for peak and off-peak electricity consumption was estimated employing aggregated data referring to four years and 40 cities. The empirical analysis has highlighted some of the characteristics of the Swiss residential electricity market. The estimated short-run own-price elasticities are −0.60 during the peak period and −0.79 during the off-peak period. Whereas in the long-run these values, as expected, are higher than in the short-run with a value of −0.71 during the peak period and −1.92 during the off-peak period. These elasticities show a high responsiveness of electricity consumption to changes in prices. Moreover, positive values of the cross-price elasticities show that peak and off-peak electricity are substitutes.

JEL classification: Q4; D1

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1. Introduction

Empirical studies of residential electricity demand have received much attention among economists since the early 1970s, spurred in large part by the 'energy crisis'. Price and income elasticities of residential electricity demand are extremely important for assessing proposals to revise electricity rate structures and for projecting future electricity demand growth. Therefore, the estimation of econometric models of electricity demand offers an interesting approach for studying the potential impacts of alternative energy policies.

In Switzerland, during the last decade, there has been a considerable amount of debate about rate reform to improve the efficiency of energy use. This debate has been caused by three main facts. First, in the last decade we observed an important growth of electricity consumption of 2% p.a. on average. Second, in 1991 the Swiss people decided in a referendum to have a ten-year moratorium on construction of new nuclear plants, thus curtailing domestic electricity supply. Third, the Swiss electric utilities face a demand that increasingly fluctuates both with season and time of day.

To date, some of the issues facing the policymakers are: Can a widespread introduction of time-of-use pricing contribute to improve the efficiency of electricity consumption in the residential sector? It is possible to encourage efficient utilization of existing electric plants and to alleviate the need for additional capacity by time-of-use pricing?

The purpose of this paper is to estimate the own- and cross-price elasticities of residential demand for electricity by time-of-use in Switzerland and thus to contribute to the rationality of the decision-making process.

The empirical analysis of residential electricity demand by time-of-use has received little attention. The econometric literature on time-of-use demand appears to consist of only a few studies [2]. These studies attempt to measure the responsiveness of residential electricity consumption to a time-of-use tariff, using data at the household level from 15 US rate experiments [3]. To our knowledge, our study is the first empirical analysis of the residential electricity demand by time-of-use, based on aggregate cross-sectional data at city or state level [4].

This paper is organized as follows. In Section 2, we present the theoretical framework and the empirical specification of the electricity demand model. In

[2] For a overview of these studies see Hawdon (1992).

[3] In the last number of decades, the U.S. department of energy promoted a number of demonstration projects to understand better the effects of time-of-use pricing on residential electricity consumption.

[4] The econometric literature on electricity demand in Switzerland consists of two main studies. The first study analyses the residential electricity demand with data at the national level, see Carlevaro and Spierer (1983) and Spierer (1988). The second study examines the residential electricity demand using data at the household level, see Dennerlein (1990). However, both studies do not analyze the electricity demand by time-of-use; rather, they aggregate the consumption during the peak and off-peak period.

Section 3, we discuss the data used in the analysis, while in Section 4, the empirical results are presented. Some concluding remarks follow in Section 5.

2. Theoretical considerations and model specification

Residential demand for electricity is a demand derived from the demand for a warm house, cooked food, hot water, etc., and can be specified using the basic framework of household production theory [5]. According to this theory, households purchase 'goods' on the market which serve as inputs that are used in production processes, to produce the 'commodities' which appear as arguments in the household's utility function. In our specific case, a household combines electricity and capital equipment to produce a composite energy commodity.

The production function of the composite energy commodity S can be written as:

$$S = S(E_P, E_O, CS) \tag{1}$$

where E_P is electricity consumed during peak period, E_O is electricity consumed during off-peak period, and CS is the capital stock consisting of appliances. Output of the composite commodity S is thus determined by the amount of electricity purchased during peak and off-peak periods as well as the quantity of the capital stock of appliances. According to Eq. (1) quantities of electricity utilized at different points in time are different inputs.

The household is also assumed to have a utility function with the usual properties of differentiability and curvature. The arguments are the composite energy commodity S and a purchased composite numeraire good X that directly yields utility, while D and G represent demographic and geographic characteristics which determine the household's preferences.

$$U = U(S, X; D, G). \tag{2}$$

The household is then assumed to maximize its utility subject to Eq. (1) and the budget constraint,

$$Y - P_S \cdot S - 1 \cdot X = 0 \tag{3}$$

where Y is money income, P_S is price of the composite energy commodity, and P_X is price of composite numeraire good X. As a result, the derived demands for electricity by time-of-use and capital stock can be obtained as:

$$E_P = E_P(P_{EP}, P_{OP}, P_{CS}, Y; D, G), \tag{4}$$

$$E_{OP} = E_{OP}(P_{EP}, P_{OP}, P_{CS}, Y; D, G), \tag{5}$$

$$CS = CS(P_{EP}, P_{OP}, P_{CS}, Y; D, G). \tag{6}$$

[5] See Dubin (1985) and Flaig (1990), for an application of household production theory to electricity demand analysis.

Eqs. (4)–(6) reflect the long-run equilibrium of the household. This model is static in that it assumes an instantaneous adjustment to new equilibrium values when prices or income change. Specifically, it is assumed that the household can change both its rate of utilization and its stock of appliances. Therefore, we can expect two types of consumer responses to an increase in the price of electricity. In the short run, the household can lower the rate with which it utilizes its stock of appliances, for example by adjusting the temperature of thermostats and water heaters. In the long run, since changes in P_{EP} and P_{EO} can result in changes in the relative prices of the inputs, they may alter the mix of the inputs for the production of the composite energy commodity S. This would presumably lead to an adjustment of the household's capital stock; less electricity-efficient appliances would be substituted by more electricity-efficient appliances.

In what follows we present the empirical model of electricity demand by time-of-use, based on Eqs. (4) and (5). The model consists of two log-linear stochastic equations for peak and off-peak electricity consumption. The major consequence, of course, is that the estimated coefficients amount to elasticities, which are assumed to be constant. Since the optimization problem refers to one household, the empirical model seeks to explain per household electricity consumption [6].

Cross-section data on appliance prices are not available. However, appliance prices faced by households can, apart from minor regional variations, be regarded as constant. Therefore, they may be excluded from the model without causing bias in estimation (see Halvorsen, 1978).

The equations to be estimated are:

$$\ln E_{Pit} = b_P + b_{P1} \ln P_{EPit} + b_{P2} \ln P_{EOit} + b_{P3} \ln Y_{it} + b_{P4} \ln HS_{it} + b_{P5} \ln HDD_{it} + b_{P6} DG_{it} + b_{P7} DR_{it} + \epsilon_{it} + U_i, \tag{7}$$

$$\ln E_{Oit} = b_O + b_{O1} \ln P_{EPit} + b_{O2} \ln P_{EOit} + b_{O3} \ln Y_{it} + b_{O4} \ln HS_{it} + b_{O5} \ln HDD_{it} + b_{O6} DG_{it} + b_{O7} DR_{it} + \epsilon_{it} + u_i \tag{8}$$

where

i = city ($i = 1, \ldots, 40$),
t = year ($t = 1987, \ldots, 1990$),
E_P = residential electricity consumption per household and year during peak period in kWh,
E_{OP} = residential electricity consumption per household and year during off-peak period in kWh,
P_{EP} = price during peak period,
P_{EO} = price during off-peak period,
Y = household personal income, approximated by the per household collected income taxes by and for municipalities,

[6] For a detailed justification of this approach see Muellbauer (1975).

HS = household size, resident population divided by the number of households,
HDD = heating degree days,
DG = 1 if the city has natural gas supply;
= 0 otherwise,
DR = 1 if all households face a two-part time differentiated tariff for electricity;
= 0 otherwise,
ϵ_{it} = is a classical disturbance with $E[\epsilon_{it}] = 0$ and $\text{var}[\epsilon_{it}] = \sigma^2$,
u_i = is an individual specific disturbance with $E[u_i] = 0$ and $\text{var}[u_i] = \sigma^2$.

We also assume that individual error components are uncorrelated with each other and are not autocorrelated.

To simplify estimation we incorporate the prices of all other consumption goods into the demand equations by deflating the electricity and capital stock prices by the consumer price index. Finally, because a system of logarithmic equations is incapable of exactly satisfying the general restrictions of consumer theory, no a priori restrictions are imposed on the Eqs. (7) and (8).

3. Data and variables

The data on electricity rates and demand during peak and off-peak periods covers four annual periods (1987–1990) and comes from 40 cities in Switzerland. They were collected using a mailed questionnaire sent to all 130 urban electric utilities of Switzerland [7]. Of the 130 questionnaires, 67 were returned, but 27 contained incomplete information. This gives a sample of 40 cities for the analysis. The data for the other variables were taken from the annual publication of the Swiss Cities Association and from the monthly publication of the Swiss Federal Institute of Meteorology.

Electricity consumption per household in city i and year t during peak and off-peak periods are the dependent variables (see Table 1). It is computed by dividing total electricity consumed in city i during each period by households by the number of households in city i. Households include single-family homes, apartments, duplexes, and condominiums as long as they have their own connection to the network.

[7] The Swiss electric power industry is composed of about 1200 firms, public and private, that are engaged in the generation, transmission, and/or distribution of electric power. There is a great divergence in size and activity of these companies. In terms of numbers, utilities exclusively engaged in the distribution of electric power are dominant, comprising 74% of the total. The majority of these 900 or so companies are municipals, and provide power to their communities exclusively. The remaining utilities operate within urban or regional areas. The activities of these electric utilities are regulated by the canton and municipal public utility commissions. These commissions govern entry, quality and condition of service including the obligation to serve all customers in the assigned service area and without discrimination. Moreover, the electricity retail rates have to be approved by these regulatory commissions.

Table 1
Description of variables (1987–1990)

Variables	1. Quartiles	Median	3. Quartile
Annual per household electricity consumption, peak period (E_P)	1854 kWh	2135 kWh	2566 kWh
Annual per household electricity consumption, off-peak period (E_{OP})	611 kWh	977 kWh	1668 kWh
Price during the peak period (P_{EP})	0.13 SwF/kWh	0.14 SwF/kWh	0.15 SwF/kWh
Price during the off-peak period (P_{EO})	0.06 SwF/kWh	0.07 SwF/kWh	0.08 SwF/kWh
Number of households (NH)	5220	6925	8330
Household size (HS)	2.01	2.21	2.37
Local income tax revenue per household (Y)	3728 SwF	4178 SwF	4645 SwF
Heating degree days (HDD)	3167	3374	3669
Annual average fixed fee (FEE)	80 SwF	102 SwF	129 SwF

The majority of electric utilities in Switzerland uses a combination of time-of-use tariff and two-part tariff. Therefore, the rate schedule typically consists of a fixed monthly charge and a constant price per kWh electricity consumed that varies according to time (day–night). This rate structure, which is used by all electric utilities of our sample, will hereafter be called two-part time differentiated tariff. Theoretically, the effect of the fixed fee on electricity consumption should be equal to the effect of income, but of opposite sign. To enforce this constraint, the fixed fee was subtracted directly from the income variable [8].

A climate variable (heating degree days) is entered in the model, which accounts for the impact of weather on the need for space heating. Because summer temperatures are not extremely high in Switzerland, there is little need for air conditioning. Thus, the model does not contain cooling degree days as a second climate variable.

Due to lack of data, we introduced the average locally collected income taxes from households as a proxy for the personal income per household, multiplied by the average number of members per household. Because tax rates differ across municipalities, this proxy for personal income per household has been corrected by a tax rate index. In view of likely measurement error, elasticities with respect to this variable are to be interpreted cautiously.

Household size is included in the model to account for the impact of the number of members per household on the demand for services provided by electrical appliances. A large family is expected to consume more electricity given a certain stock of appliances in the household.

A dummy variable is used to distinguish cities offering the two-part time differentiated tariffs only to customers who use a lot of electricity during the

[8] For an interesting discussion about the appropriate price structure to include in an electricity demand, see Taylor (1975) and Nordin (1976).

off-peak period, for example for electric heating. Therefore, in these cities there are customers on a two-part rate schedule and customers on a two-part time differentiated rate schedule.

A second dummy variable was introduced in an attempt to differentiate cities with natural gas supply [9]. This allows us to estimate the effect of natural gas availability on the demand for electricity.

With regard to choice of econometric technique, it should be noted that the three most widely used techniques of panel data analysis are: the OLS model, the least-squares dummy variable (LSDV) model, and the error components model (EC) [10]. In the present study, Eqs. (7) and (8) were estimated by the OLS method and by the EC method, which includes a cross-sectional error component [11].

According to Halvorsen (1978) and Baltagi and Griffin (1984) the OLS model seems to yield the closest estimate of long-run response, whereas the EC model seems to yield short-run response if the variance of the individual random effects is large and long-run response if the variance is small [12].

Finally, since the same explanatory variables appear in the two log-linear demand equations, it is not possible to improve the separate least-squares estimation using a seemingly unrelated regression technique [13]. Table 1 gives some details on the variables employed in the analysis.

4. Estimation results

The results presented in Table 2 are satisfactory in so far as the own-price elasticities and the cross-price elasticities, which form the primary concern of this study, are generally significant and carry the expected signs in both models.

According to Baltagi and Griffin (1984), if the between variation (i.e., the variation between the cities) for the relevant explanatory variables in the model greatly exceeds the within variation (i.e., the variation over time), and the variance of the individual random effects is large then OLS becomes a preferred estimator of the long-run response. In our model the most important explanatory variables

[9] Generally, only some quarters of these cities (about 30% of all Swiss cities) are provided with natural gas capabilities. However, the majority of Swiss urban households lives in rented apartments, thus, they do not really have a choice concerning their energy source. Therefore, in the Swiss residential sector natural gas seems to be a poor substitute as an energy source.

[10] See Balestra and Nerlove (1966) and Greene (1990).

[11] Since a time-series error component was not supported by temporal LSDV analysis, it was not observed in the present study.

[12] In the OLS model, the between-group and the within-group variation is added up. The GLS model is a compromise solution to this all or nothing way, utilizing the between-group variation, which considers underlying structural changes across cities.

[13] For the same econometric argument we do not need to estimate the demand equation for capital stock (6) together with the demand equations (4) and (5).

Table 2
Estimated residential time-of-use electricity demand equations (standard errors in parentheses)

Independent variables	Dependent variables			
	ln peak kWh OLS	ln peak kWh EC	ln off-peak kWh OLS	ln off-peak kWh EC
Constant	5.95	5.97	−1.75	5.13
	(1.08)	(0.96)	(2.13)	(1.08)
ln P_{EP}	−0.71	−0.60	2.16	0.91
	(0.20)	(0.27)	(0.39)	(0.34)
ln P_{EO}	0.65	0.40	−1.92	−0.79
	(0.27)	(0.27)	(0.52)	(0.31)
ln Y	0.04	0.03	−0.03	0.03
	(0.07)	(0.07)	(0.13)	(0.77)
ln HS	0.63	0.81	2.15	1.11
	(0.17)	(0.25)	(0.33)	(0.34)
ln HDD	0.16	0.01	0.75	−0.00
	(0.11)	(0.07)	(0.22)	(0.08)
DG	0.01	0.00	0.14	0.52
	(0.04)	(0.08)	(0.85)	(0.16)
DR	−0.15	−0.16	0.312	0.16
	(0.05)	(0.08)	(0.09)	(0.17)

are electricity prices by time-of-use, which allow us to compute price elasticities. Further, we observe in our sample that the between variation of these price variables is much larger than the within variation and that the variance of the individual random effects is large. Therefore, the coefficients estimated using OLS have to be interpreted as long-run elasticities whereas those of the EC model should be viewed as short-run elasticities. Moreover, the presented standard errors for the OLS model are calculated from (White's) heteroscedastic-consistent variance–covariance matrix.

The estimated short-run own-price elasticities are −0.60 during the peak period and −0.79 during the off-peak period. Whereas in the long-run these values, as expected, are higher than in the short-run with a value of −0.71 during the peak period and −1.92 during the off-peak period. These elasticities show high responsiveness of electricity consumption to changes in peak and off-peak prices. Moreover, in both models the positive values of the cross-price elasticities suggest peak and off-peak electricity to be substitutes [14]. Moreover, raising the peak price

[14] The estimated price elasticities are higher than those found in other studies. However, a comparison of the results is difficult, and typically inconclusive since models, data, and time periods used are not similar. Further, the majority of the studies on time-of-day pricing of electricity have their empirical basis on experiments where consumers were faced with a variety of schedules and prices with, however, the guarantee that they would not have to pay more than the usual amount for their electricity consumption.

of electricity appears to have a strong long-run effect on the consumption of off-peak electricity. Thus time-of-use pricing seems to provide consumers with a strong incentive to find a substitute for peak-period consumption, serving to reduce the need for extra capacity.

The demands for electricity during the peak and off-peak period are not responsive to the level of income (Y). However, both estimates are likely to be biased towards zero. As is well known, measurement error in the regressor variable causes downward bias in the slope estimate in the case where the error is uncorrelated with the true value of the regressor. This bias becomes more important if there is positive correlation. In Switzerland, where local jurisdictions compete for wealthy taxpayers while the tax function ceases to be progressive at the high end, measurement error in the proxy variable 'tax revenue from income' and true income may well be positively correlated.

The heating degree day variable (HDD) has been included in the models in an effort to control for the impact of weather on electricity demand. Heating degree days should influence electricity demand positively, since electricity is a relatively frequent choice for heating. In the OLS model the weather is seen to influence off-peak electricity consumption much more than peak consumption, as shown in Table 2. This result may be due, in part, to the use of electricity heating appliances that, during the off-peak period, store electricity for consumption in the peak period.

The estimated coefficient of household size (HS) is positive in both models. Thus, as family size increases, there is a tendency to use more electricity. This effect is much stronger in off-peak consumption than in peak consumption. A possible explanation hinges on intensity of use. A large family may use their appliances during the off-peak period more intensively than during the peak period, when few of their members are at home.

Availability of natural gas (DG) does not seem to play a role in determining electricity demand. Finally, the dummy variable for full availability of the two-part time differentiated tariff (which is equal to 1 for cities offering this tariff to all customers) has a significantly negative coefficient in both peak-period equations, and a significantly positive coefficient in the OLS off-peak equation and a not significant one in the EC model. This result may be due to the fact that the percentage of households having an electric heating system is greater in cities offering a two-part time differentiated tariff to all customers than in areas where this tariff is only available to selected groups of households.

5. Summary and conclusions

In this study, we have examined the residential demand for electricity by time-of-day in Switzerland. For this purpose, a model of two log-linear stochastic equations for peak and off-peak electricity consumption was estimated employing aggregated data referring to four years and 40 cities.

The empirical analysis has highlighted some of the characteristics of the Swiss residential electricity market. The estimated short-run own-price elasticities are −0.60 during the peak period and −0.79 during the off-peak period. In the long-run these values are higher than in the short-run, with values of −0.71 during the peak period and −1.92 during the off-peak period. These elasticities suggest a high responsiveness of electricity consumption to changes in prices. Moreover, the positive values of the cross-price elasticities point to a great deal of substitution. Household income, imperfectly measured, seems not to affect electricity demand.

From the standpoint of conserving end-use electricity, it is of great interest to know the peak and off-peak demand elasticities with respect to individual electricity prices. The fact that the own-price elasticities are all negative and that the cross-price elasticities are all positive has an important implication for conservation. It suggests that pricing policy can be an effective instrument for achieving electricity conservation and that time-of-use pricing in particular can contribute to more efficient utilization of existing production capacity, allowing the build-up of additional capacity to be postponed.

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