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Demand for Electric Energy in the Presence of a two-block Declining Price Schedule

by

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DISCUSSION PAPERS

Demand for Electric Energy in the Presence of a two-block Declining Price Schedule

CENTRE OF PLANNING AND ECONOMIC RESEARCH

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ABSTRACT

The paper presents a model for obtaining unbiased and efficient estimates of the parameters of demand for electricity in the presence of a two block declining price schedule. The estimation method is based on ordering of price regimes by output level and forming the likelihood function. A Generalised Leontief cost function is specified and the resulting input demand for electricity is estimated for the Greek industrial sector. Empirical results show significant divergence between OLS and ML estimates based on the entire price schedule.

1. INTRODUCTION

In formulating a model for electricity demand, one must take into account the fact that electricity prices are not in general exogenous but rather functions of the quantities consumed.

The existence of non-linear prices has important theoretical implications for the equilibrium of the optimising agent, since the solution of the minimisation problem no longer gives a conventional overall input demand function due the complexity of the budget set.

Although researchers investigating the demand for electric energy have been long aware of the endogeneity of prices, the theoretical issues received very little attention. Most of the work in the field focuses the attention on finding a practically acceptable specification for the price variable in a linear regression model. The simplest specification adopted in empirical work on electricity demand is the average price specification. An ex post average price is constructed by dividing total expenditure of a group of customers by quantity consumed. The prevailing argument however, since Houthakker's earlier work (1951) was that the marginal price is relevant in the demand function because the optimising agent achieves equilibrium by equating cost and utility at the margin. It is however obvious that both average and marginal specifications are not adequate predictors of quantity variation their use being linked to endogeneity and specification problems.

Consider the simple example of a two block declining price structure given by:

For $X_1 \leq \overline{X}_1$ the price is P_1 and for units of in excess of $\overline{X}_1$ the price is $P_1' < P_1$. In this case P_1' is the marginal price and $(P_1\overline{X}_1 + P_1'(X_1 - \overline{X}_1))/X_1$ is the average price.

It is possible in this case to have a combined change in P_1 and P_1' which would lead to a change in X_1 but leave the average price unchanged. Also we could have a change in both P_1' and $\overline{X}_1$ with no resulting change in X_1 but relating to a different average price. In a similar way a change in X_1 may be due to a change in P_1 with the marginal price remaining unchanged.

The fact that neither average nor marginal price by itself determines optimising demand was realised by many authors. Taylor (1975) demonstrates some technical aspects of the optimisation in the presence of a declining two block tariff structure but does not indicate an adequate estimation procedure. Recent studies attempt to include more than one characteristics on the price structure. McFaden, Puig and Kirshner (1972) associated individuals consumption with both actual average price paid and the applicable marginal block rate, whereas Taylor, Blattenberger and Verleger (1977) employed total actual expenditure of each individual and the consumer's marginal block rate. This last approach amounts to what has been known in the empirical literature on labour supply as linearisation of the budget constraint. In other words the piece-wise linear budget line is approximated by a linear one passing through the observed consumption point and having slope the one given by the price of the applicable marginal block. Assuming that every individual's observed and optimising demand are on the same budget segment, the above approach involves no endogeneity or specification errors. However observed demand for certain individuals may be a point on a different budget segment than the one associated with optimising demand. The above approach although a step forward does not provide, in this case, an adequate framework for unbiased estimates since specification and endogeneity bias are still present.

Econometric estimation of the parameters of economic models in the presence of non-linear pricing that overcomes the above problems originates in the work of Burtless and Hausman (1978) and Wales and Woodland (1979). These authors and also Hausman (1981), Zabalza (1983), Blomquist (1983) and Balfoussias (1990) have proposed estimators for labor supply with taxes. Hausman (1980) estimates housing demand parameters under a discontinuous budget constraint. Balfoussias (1986) describes equilibrium in a production context under three types of energy price schedules and explores the question of ordering price regimes by output or technology.

The purpose of this paper is to specify and estimate an econometric model for the industrial demand for electricity in Greece with a view of taking into account the fact that the choice of individual firm depends on the entire price schedules which comprise the budget set.

The paper is organised as follows. In Section 2 we present the main theoretical results on the basis of which appropriate estimation techniques may be based. In Section 3 an econometric model for industrial demand for electricity under two-block pricing is specified. In Section 4 the model is estimated for a sample of industrial users charged on two-block tariff system and finally section 5 summarises the main results and discusses directions for further research.

2. SOME THEORETICAL RESULTS ON EQUILIBRIUM UNDER NON-LINEAR PRICING

Let the production function take the form $y = f(x_1, x_2, \theta)$, where y stands for a single output, x_1 and x_2 represent two factors of production the first of which is electricity and θ stands for a vector of technological parameters. It is assumed that x_2 can be purchased in unlimited quantities at p_2, whereas x_1 is purchased according to a two-part tariff. In particular let $\bar{x}_1$ stand for the fixed number of units in the primary block. Then the consumer's tariff consists of: (a) a unit charge, p_1, for each of the first $\bar{x}_1$ units and (b) a lower unit charge $p'_1 < p_1$, for each unit demanded in excess of $\bar{x}_1$. The effect of the piece-wise linearity in prices is to create a non-convex budget set.

The cost minimizing decisions of individual producers are described by the expression :

$$\min\{\; C_0 = c(p_1, x_1, \bar{x}_1) + c'(p'_1, x_1, \bar{x}_1) + p_2 x_2 \;\mid\; y = f(x_1, x_2, \theta)\}$$

$$\text{where } c(p_1, x_1, \bar{x}_1) = \begin{cases} p_1 x_1 & \text{if } x_1 \le \bar{x}_1 \\ p_1 \bar{x}_1 & \text{if } x_1 > \bar{x}_1 \end{cases} \text{ and } c'(p'_1, x_1, \bar{x}_1) = \begin{cases} 0 & \text{if } x_1 \le \bar{x}_1 \\ p'_1(x_1 - \bar{x}_1) & \text{if } x_1 > \bar{x}_1 \end{cases} \tag{1}$$

The optimisation process is in effect divided into three parts:

(a) minimize cost under the constraint $x_1 \le \bar{x}_1$

(b) minimize cost under the constraint $x_1 > \bar{x}_1$

(c) compare the two optima to derive the global optimum.

Under the constraint $x_1 \le \bar{x}_1$ the Lagrangian function takes the form

$$Z = p_1 x_1 + p_2 x_2 + \lambda(y - f(x_1, x_2, \theta) + \mu(x_1 - \bar{x}_1)) \tag{2}$$

The Kuhn-Tucker conditions for minimum are:

$$\partial Z/\partial x_1 = 0, \quad \partial Z/\partial x_2 = 0, \quad \partial Z/\partial \lambda = 0, \quad \partial Z/\partial \mu \le 0, \quad \mu \partial Z/\partial \mu = 0 \tag{3}$$

and the resulting cost function is given by

$$C = g(p_1, p_2, y, \theta) \quad \text{or} \quad C = h(p_1, p_2, y, \bar{x}_1, \theta) \tag{4}$$

where $g(.)$ is a cost function with conventional properties and $h(.)$ takes the form

$$h(p_1, p_2, y, \bar{x}_1 \theta) = p_1 \bar{x}_1 \quad + \quad p_2 x_2(y, \bar{x}_1, \theta) \tag{5}$$

Under the constraint $x_1 > \bar{x}_1$ the Lagrangian function becomes

$$Z=\bar{x}_1(p_1-p_1')+p_1'x_1+p_2x_2+\lambda(y-f(x_1,x_2,\theta)+\mu(x_1-\bar{x}_1)) \qquad (6)$$

The Kuhn-Tucker conditions for minimum are:

$$\partial Z/\partial x_1=0,\quad \partial Z/\partial x_2=0,\quad \partial Z/\partial\lambda=0,\quad \partial Z/\partial\mu=0 \qquad (7)$$

and the resulting cost function is given by:

$$C'=g'(p_1,p_1',p_2,y,\theta,\bar{x}_1)$$

or $$C'=g(p_1',p_2,y,\theta)+\bar{x}_1(p_1-p_1') \qquad (8)$$

where $g(.)$ has the usual properties. As a result the cost function associated with global minimum defined by $Cg=\min\{C;C'\}$ may be written as

$$Cg=\min\{[g(p_1,p_2,y,\theta) \text{ or } h(p_1,p_2,y,\bar{x}_1,\theta)] \quad ; \quad g'(p_1,p_1',p_2,y,\theta,\bar{x}_1)\} \qquad (9)$$

Expression (9) describes the possible outcomes of the cost minimisation problem in terms of cost functions for a two-segment, non-convex budget set.

By convexity and monotonicity of the production function it follows that $g(.)<h(.)$ for any set of values of the parameter vector and therefore $\bar{x}_1$ cannot represent the globally optimal choice. As a result equation (9) can be reduced to

$$C_g=\min\{g(p_1,p_2,y,\theta);[(p_1',p_2,y,\theta)+\bar{x}_1(p_1-p_1')]\} \qquad (10)$$

A number of observations can be made regarding the functions representing local optima in (10). In particular depending on

$p_1,p_2,p_1',y,\theta,\bar{x}_1$, $\quad C_g=g(.)$, *or* $C_g=g'(.)$, *or* $C_g=g(.)=g'(.)$ is true.

Input demand functions $X=f(p_1,p_2,p_1',y,\theta,\bar{x}_1)$ can be derived by differentiation of C_g with respect to p_i. It follows that while conventional demand functions may be constructed for each continuous segment of the budget constraint, the overall input demand functions are non-analytical. Comparative static properties are also non-conventional since $X=f(p_1,p_2,p_1',y,\theta,\bar{x}_1)$ will be discontinuous and non differentiable for a small area around $\bar{x}_1$. They will also be multivalued, with more than one equilibrium quantity consistent with certain configurations of prices and output.

It has been shown (Balfoussias 1986) that under homothetic technology there exists a level of output y^* defined by $F=g(.)-g'(.)=0$ which divides behaviour in a way that equilibrium is on regime p_1/p_2 for all $y<y^*$ and on regime p_1'/p_2 for all $y>y^*$. This ordering of regimes can be the basis of maximum likelihood estimation.

3. AN ECONOMETRIC MODEL OF THE DEMAND FOR ELECTRICITY IN THE PRESENCE OF A TWO-BLOCK DECLINING PRICE SCHEDULE

3.1. The Deterministic Model

Assume that there exists a well behaved production function defined at the firm level, relating output to the services of a number of inputs, including energy inputs. By duality theory the production technology can be represented by a cost function of the form

$$Cf = C(p_{if} \dots p_{nf}, Q_f) \tag{11}$$

where p_{if} is the price of the ith input of the f firm and Q_f the firm's output.

Imposing homothetic weak separability in energy inputs the cost function takes the form

$$C_f = C[\, p_{Ef}(p_{Eif}, \dots, p_{Emf}), p_{xf} \dots, p_{nf}, Q_f] \tag{12}$$

where p_{Ef} is a price aggregator function for the energy prices $p_{Eif} \dots p_{Emf}$.

Equation 12 allows one to represent total energy cost by an arbitrary cost function of the form

$$C_{Ef} = g(p_{E1} \dots p_{Em}) Q_{Ef} \tag{13}$$

where Q_{Ef} is the total energy measure representing the assumed energy quantity aggregator. We are assuming in 13 that the energy cost function is linear homogeneous in aggregate Q_{Ef}.

Consider the case where a firm can choose among two types of energy inputs namely, Electricity (E_1), and liquid fuels (E_2). Let p_1, p_2 represent the respective prices.

Let us now take into account the fact that electricity is purchased according to a two block declining price schedule, so that quantities of electricity $E_1 \leq \overline{E}_1$ are charged at a price p_1 and quantities of $E_1 \geq \overline{E}_1$ at a price p_1'.

It was shown in the previous section that the cost function takes the form

$$C_{Ef}global = \min\{C_{Ef}; C_{Ef}\} \tag{14}$$

Ignoring for simplicity the subscript f the local cost functions are given by

$$C_E = g(p_1, p_2, Q_E, \theta)$$

and $$C_E' = g(p_1', p_2, Q_E, \theta) + \overline{E}_1(p_1 - p_1') \tag{15}$$

Assume now that technology is represented by a Generalized Leontief cost model. Equation 14 takes the parametric form

$$C_E = \min\{\sum\sum b_{ij}(p_i p_j)^{1/2} Q_E ; \sum\sum b_{ij}(p_i p_j)^{1/2} Q_E + \overline{E}_i(p_i - p_i')\} \qquad (16)$$

As shown in the previous section the assumption of homothetic technology is sufficient condition for ordering the two price regimes and therefore the two cost functions, by the level of $Q_{E/}$. In particular, double equilibria situation is given by

$$F = C_E - C_E' = 0 \qquad (17)$$

and under the assumptions maintained so far, F defines an implicit function of the form

$$Q_E^* = Q_E(p_1, p_1', p_2, \overline{E}_1, b_{ij}) \qquad (18)$$

In the present case we can solve for Q_E^* explicitly to get

$$Q_E^* = \overline{E}_1 f(p_1 - p_1')/[(b_{11}(p_1 - p_1') + (p_1^{1/2} - p_1'^{1/2})(b_{12} p_2^{1/2})] \qquad (19)$$

The two cost functions in 16 can therefore be ordered as follows:

$$C_E = \sum\sum b_{ij}(p_i p_j)^{1/2} Q_E \quad for \quad Q_E < Q_E^* \quad p_i, p_j = p_1, p_2$$

$$C_E = \sum\sum b_{ij}(p_i p_j)^{1/2} Q_E \quad for \quad Q_E > Q_E^* \quad p_i', p_j = p_1, p_2 \qquad (20)$$

Differentiating with respect to p_1 and p_1' we get the following demand for Electricity model

$$E_1 = [b_{11} + b_{12}(p_2/p_1)^{1/2}] Q_E \quad for \quad Q_E < Q_E^*$$

$$E_1 = \left[b_{11} + b_{12}(p_2/p_1')^{1/2}\right] Q_E \quad for \quad Q_E > Q_E^* \qquad (21)$$

3.2. The Stochastic Model

Given a sample of observations on $E_1, p_1, p_1', p_2, \overline{E}_1$ and Q_E one can estimate the parameters of (21) by means of maximum likelihood techniques.

Assume therefore that observed electricity consumption deviates from theoretically optimum levels by a random term u, attributed to an optimization error. We shall assume that u is normally distributed with zero mean and variance σ_u^2. Under this stochastic specification our model takes the form

$$E_1 = [b_{11} + b_{12}(p_2/p_1)^{1/2}] Q_E + u \quad for \quad Q_E < Q_E^*$$

$$E_1 = \left[b_{11} + b_{12}(p_2/p_1')^{1/2}\right] Q_E + u \quad for \quad Q_E > Q_E^* \qquad (22)$$

Given values of the predetermined variables, a certain value of E_1 can be generated by the first regime with probability $pr(Q_E < Q_E^*) = \lambda$ or by the second regime with probability $pr(Q_E > Q_E^*) = 1 - \lambda$.

The probability density function of observed E_1 taken at random is the mixture of the density of E_{11} under the first regime and the density of E_1 under the second regime with weights λ and $1 - \lambda$ respectively and is also normally distributed.

Under our normality assumptions maximization of the log likelihood function is equivalent to minimisation of the sum of square residuals (SSR). Therefore in order to obtain efficient estimates for the unknown parameters $b_{11}, b_{12}, \sigma u$ we need an appropriate algorithm to compute and minimize (SSR). To determine the price regime for each observation in the sample we calculate Q_E^* and compare it to Q_E observed. Given values of the parameters $\hat{E}_1$ is calculated and SSR computed. A number of iterative methods are available for minimizing a function with respect to a vector of parameters.

4. EMPIRICAL APPLICATION

4.1. The Data

The bulk of electricity consumption in Greece is priced according to some type of block tariffs. Residential consumers face an increasing price schedule, industrial consumers and in particular medium voltage consumers are charged according to a declining two block price schedule. The latter category of consumers was the basis of our estimation. In particular the price schedule consists of

(a) A service capacity charge.

(b) A unit charge p_1 for each unit in the first block.

(c) A unit charge $psuer'_1 < p_1$ for each subsequent unit taken that is for each unit in the second block.

Blocks are not however fixed by the electricity authorities but differ among individual firms adopting the tariff depending on maximum demand, where maximum demand is usually defined as the largest number of units supplied during a period of thirty consecutive minutes. Maximum demand also determines the service capacity charge along with other technical characteristics. In other words although unit charges are identical for all consumers each firm faces it's own price schedule.

In what follows the price schedule is considered exogenous to the cost minimizing decisions of the firm. Other assumptions may also be explored ie link maximum demand with certain parameters of the cost function or treat it as a separate input. For the purposes of this econometric exercise however we assume that maximum demand is a technical characteristic independent of total quantity consumed.

Individual data on consumption levels, technical characteristics and electricity prices were offered by the Greek Public Power Corporation. We selected a random sample consisting of 550 monthly observations. Energy quantity aggregate was constructed as a divisia index of electricity consumption and consumption of liquid fuels. The latter refers to average monthly consumption at the three digit level.

4.2. Empirical Results

The parameters of the generalised Leontief demand function for electricity were first estimated by OLS using a marginal price specification. This estimation serves both as a means of obtaining initial guesses for the parameters of the model and as a reference point for comparisons.

$$E_1 = [\ -6750 + 21366\ (P_2/P_1)^{1/2}\ ]\ QE$$

$$\quad (1.84) \quad (2.95) \qquad\qquad R_2=.42$$

The numbers in parentheses are t statistics.

Our Maximum likelihood estimates were obtained by the Davidson-Fletcher- Powell method which is a gradient method and requires first order partial derivatives. OLS estimates were used as initial guesses for the parameters of (22) . A starting value for σ^2_{u1} was again based on the standard error of the OLS estimation. Maximum likelihood estimates are presented in Table 1.

TABLE 1

	Initial guesses	Estimates
b_{11}	-6750	-7925
b_{12}	21366	33388
Number of iterations:	40	

It is obvious that there is significant divergence between OLS estimates and ML estimates based on the entire price schedule. This divergence can be interpreted as a measure of the bias resulting from the omission of information contained in the price schedule. It is also interesting to notice that 15 % of the sample has an optimizing block different from the observed one.

Elasticity estimates cannot be calculated using the parameter estimates with observed data, because comparative static effects must also take account of the non-convexity of the budget set. To obtain quantity responses to price changes, we use the optimising parameters, in order to simulate the effects of particular changes in exogenous variables. To this effect we used price schedules for the same individuals referring to the following month for which prices were changed. The results of this simulation are reported in Table 2.

TABLE 2

	Initial price	New price	Average change of optimal quantity (%)
Firms in first block	9.36	10.54	.36
Firms in second block	6.24	7.04	.51

Average price responses are calculated from Table 2 at .33 and .47 respectively. These results indicate that industrial demand for electricity in Greece has a price elasticity less than unity.

5. CONCLUSIONS

In this paper we have presented a model for estimating the parameters of a demand function for electric energy by industrial users charged under a two-block declining price schedule. A generalised Leontief cost function was specified which enables ordering of regimes by output. Our application has shown that there is significant divergence between OLS estimates based on marginal price specification and ML estimates taking into account the entire price schedule. The empirical evidence has shown that consumption data relating to complex price schedules should not be used to estimate price elasticities on the basis of ex post average prices.

The methodology developed here can easily be applied to the case of household demand for electricity, where usually increasing price schedules are employed, and indeed to the problem of demand for telephone services.

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