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DETERMINANTS OF THE LONG-RUN DEMAND FOR ELECTRICITY[1]

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1. Introduction

This study is concerned with residential electricity demand. This demand has two features which require modification of commonly used commodity demand models. First, electricity consumption is a derived demand, with consumption patterns determined by the portfolio and operating characteristics of appliances held by the household, as well as by current household activities. Consumers will respond to changes in energy prices by changing the intensity of use of appliances they hold, and in the longer run by changing their appliance portfolio.

Second, most residential consumers face nonlinear "declining block" rate schedules in which average and marginal cost per kilowatt-hour (KWH) decline as monthly consumption rises. The response of a classical economic consumer to such a price structure cannot normally be expressed in terms of a summary price index such as average price, but depends on the entire rate structure.

Non-linear electricity rate schedules also introduce several econometric complications. Most empirical studies of electricity demand have drawn on cross-section or time-series data at the national, state, or utility level. These data confound the effects of aggregation and consumer response to the rate structure. Second, at either the household or aggregate levels, a model which regresses average consumption on average or marginal price at the point of consumption introduces a simultaneity problem, since a consumption level that is higher than that explained by the econometric model will cause the average or marginal cost to be lower. The result will be a spurious negative correlation of consumption and price, yielding an overestimate of the price elasticity of demand.

2. Modelling Household Electricity Consumption

The electricity demand model most commonly used in the literature explains consumption as a direct function of rates, income, climate, and socioeconomic factors, without taking into account the intermediating effect of appliance holdings. These can be interpreted as "reduced form" models in which optimization of the appliance portfolio is implicitly assumed. Table 1 summarizes selected "reduced form" price and income elasticities from recent surveys (Taylor, 1975, 1975a, and Electric Utility Rate Design Study, 1977) and more recent studies. Note that electricity demand appears to change slowly in response to price or income changes, with low short-run elasticities, but substantial long-run elasticities. The reported studies have used either average price, or marginal price defined by the tail block rate or an intra-Typical-Electric-Bill (TEB) rate, as a price variable. Consequently, these models are unable to capture, in any detail, the impact of rate structure on demand. In particular, they do not permit a separation of the effects of the level of the rate schedule and the rate of decline of marginal price.

Halvorsen (1976) fits a demand system in which the rate structure is approximated by a two-parameter family, log (electricity bill) = a + b log KWH . In this formulation, the overall level of rates and the rate of decline of marginal price could be analyzed as separate policy instruments. However, this family of parametric rate structures is quite restrictive, requiring marginal price to be a constant proportion of average price, and Halvorsen's econometric method fails to take into account inter-state variations in the parameters a and b .

A modification of the Halvorsen model which corrects some of its difficulties has been fitted by McFadden and Puig (1975). This demand model consists of an equation specifying the rate structure for each state as a three-parameter function of TEB's of 250,500 and 750 KWH per month, and an equation specifying the annual average of monthly consumption for each state as a function of exogenous factors and the price schedule. The parameterized rate schedule was used to provide estimates of the average price and marginal price of electricity at the average demand level for the state. Demand was assumed to have a log-linear form, and was estimated by two-stage least squares, with the non-price right-hand-side variables and the TEB's used as instruments. The coefficients of price and income, given in Table 1, are generally comparable to those obtained in earlier studies.

3. Electricity Consumption Conditioned on Appliance Holdings

This study utilizes a structural model in which one equation describes intensity of use given appliance holdings, and a second describes the choice of appliance portfolio. To avoid the confounding effects of aggregation, the model is fitted to data on individual households. The basic data source for this study is a 1975 survey of 3249 households carried out by the Washington Center for Metropolitan Studies (WCMS) under the direction of Pamela Kacser of the Federal Energy Administration (see also Newman and Day, 1975). A stratified random sample design was used, with an oversampling of urban lower income groups. The survey collected data on socioeconomic and demographic characteristics of each household, and made an inventory of appliance holdings. Household electric bills and killowatt-hours consumption were collected monthly from the utilities providing service to the households.

Lack of information from the survey forms made it impossible to identify and collect the exact rate schedules faced by each sampled household. TEB's for 1975 at consumption levels of 100, 250, 500, 750, and 1000 KWH per month were collected for each city (or nearby city) occurring in the sample.[2] These bills give the general shape of the rate schedule, including marginal price and the rate of decline of the schedule, but do not identify "connect" or service charges, block rate boundaries, or special appliance rates.

Three price measures were assumed to

summarize, or parameterize, the rate schedule faced by each household: marginal price at an intermediate consumption level (defined to equal marginal price between TEB's at 500 and 750 KWH per month), rate of decline of marginal price (defined to equal marginal price between TEB's at 750 and 1000 KWH per month, divided by marginal price between TEB's at 500 and 750 KWH per month), and average price (defined as the measured average monthly consumption of the household, with cost obtained by linear interpolation between adjacent TEB's).

Consider first the equation for electricity consumption conditioned on appliance holdings. The fitted equation is given in Table 2. The coefficients of the three price variables and income are interpretable as demand elasticities, as a result of the logarithmic specification. If cross-sectional price and income differentials have been fairly stable over time, these elasticities can be interpreted as measures of long-run response.

The equation in Table 2 is estimated by an instrumental variables method to avoid simultaneity caused by correlation of measured average price and the unobserved residual. A predicted consumption level is obtained by regressing log average monthly consumption on all TEB's (which are uncorrelated with the error term since they are measured at fixed consumption levels), and all right-hand-side variables in Table 2 except average price. This predicted consumption level is used to interpolate the TEB's to obtain a predicted average price, which is used as an instrument for measured average price. Under normal regularity conditions, this method yields consistent estimators of the demand parameters. The statistical model can be written

(a) $y_i^* = x_i^*\alpha + z_i\beta$

(b) $x_i^* = f(y_i^*, w_i)$

$y_i = y_i^* + \varepsilon_i$

where i is an index of observations, x_i^* is the exact price (unobserved), y_i^* is the exact quantity demanded in the absence of the effect of unobserved exogenous variables, z_i is a vector of observed exogenous variables, w_i is a vector of observed TEB's, and y_i is observed demand. Equation (a) gives the demand function, with parameters α and β to be estimated. Equation (b) gives the known, non-linear relationship between quantity and price. The estimation technique first regresses observed output on the TEB's and exogenous variables,

(c) $y_i = w_i\gamma + z_i\delta + \eta_i$,

yielding fitted values $\hat{y}_i$ for observed demand. Then, $\hat{x}_i$ is computed from the equation $\hat{x}_i = f(\hat{y}_i, w_i)$. Finally, the normal equations

$$\begin{pmatrix} \sum_i \hat{x}_i y_i \\ \sum_i z_i' y_i \end{pmatrix} = \begin{pmatrix} \sum_i \hat{x}_i x_i & \sum_i \hat{x}_i z_i \\ \sum_i z_i' x_i & \sum_i z_i' z_i \end{pmatrix} \begin{pmatrix} \hat{\alpha} \\ \hat{\beta} \end{pmatrix}$$

are solved for the parameter estimates. To establish the consistency of this procedure under normal regularity conditions, it is sufficient to show

$$\begin{aligned} 0 &= \operatorname{plim} \frac{1}{N}\sum_i \varepsilon_i \hat{x}_i \\ &= \operatorname{plim} \frac{1}{N}\sum_i \varepsilon_i f(\hat{y}_i, w_i) \\ &= \operatorname{plim} \frac{1}{N}\sum_i \varepsilon_i \operatorname{plim} f(\hat{y}_i, w_i) \\ &\quad + \operatorname{plim} \frac{1}{N}\sum_i \varepsilon_i [f(\hat{y}_i, w_i) - \operatorname{plim} f(\hat{y}_i, w_i)] \quad . \end{aligned}$$

The first limit in the last equation is zero, under normal regularity conditions, by Kolmogorov's strong law of large numbers (Rao,1973, 2c.iii). The second limit is zero since the term in brackets has probability limit zero (Rao, 1973, 2c.x).

Dummy variables indicating appliance holdings are treated as predetermined, and independent of the stochastic term in the average consumption equation, in this procedure. This assumption is valid provided the unobserved variables entering the determination of appliance portfolio are independent of the unobserved variables entering the determination of average consumption conditioned on appliance portfolio — an assumption that demand has a recursive, or causal chain, structure. If the assumption is incorrect, estimates will be biased. The bias could be eliminated, asymptotically, by using instrumental variables for the appliance portfolio dummies; the estimated probabilities of alternative portfolios, calculated for each household, are promising instruments.

The log linear model specification yields residuals which appear to be homothetic, and permits easy interpretation of parameters. However, the specification implies that the effects of appliances are multiplicative. A more natural specification of additive appliance effects yields a non-linear model whose estimation was beyond the scope of this investigation.

There is some evidence (Anderson (1973), Baughman-Jaskow, (1974)) that the price elasticity of electricity consumption varies with appliance portfolio. One would expect the introduction of electric space heat into the appliance portfolio, resulting in a substantial segment of consumption that is visible to the consumer and easily controlled, would raise the price elasticity. Air conditioning would be expected to have a similar effect.

To test these hypotheses, the coefficient of marginal price in the equation above was disaggregated by type of appliance portfolio held. The results are given in Table 3. The price elasticities are summarized in Table 4, and support the hypothesis that the presence of electric space heat raises price elasticity. However, electric water heat or air conditioning appear to have no significant effect on elasticities.

4. Appliance Saturations

One of the primary mechanims for long-run response to a change in energy prices is a change in the portfolio of appliance holdings. The totally rational economic consumer will evaluate each possible portfolio in terms of the utility of the services it can provide and the disutility of the goods foregone to pay the initial and operating cost of the portfolio. If there is no uncertainty and markets for borrowing are perfectly competitive, a portfolio will be assessed in terms of its "life-cycle" cost; i.e., in terms of the present value of initial and operating costs. With uncertainty about future prices and appliance operating efficiencies, and imperfect intertemporal markets, each consumer will have an evaluation of life-cycle costs dependent on his expectations and on his discount rate. Further, in the absence of complete rationality, the consumer is likely to respond to simpler market indicators than a fully articulated life-cycle cost.

The presence of unobserved variations across individuals in the evaluation of the benefits from alternative appliance portfolios, as well as differing evaluations of life-cycle costs, will lead utility maximizers to divide themselves among alternatives in shares which are sensitive to observed price differentials and other socio-economic and demographic factors. One statistical model consistent with such behavior is the multinomial logit choice model treated by McFadden (1973). We adopt this approach. Saturation equations are estimated for the presence of air conditioning and for water and space heating fuel types. Choice of cooking and clothes-drying fuel type have not been modeled.

Econometric analysis of appliance choice behavior presents several problems. First, the components of "life-cycle" appliance cost are generally not all observable. Survey data, and the WCMS survey specifically, do not provide sufficient information to determine vintage, initial price, or operating efficiency of individual appliances. To the extent that initial costs and operating efficiencies for each appliance portfolio are uniform over the sample, the omission of initial costs and the introduction of a simple price per KWH measure will not bias the coefficient of price response, as the remaining cost effects will be absorbed in the price coefficient and in the alternative-specific shift coefficients. This case is not unreasonable for cross-section analysis, but is probably implausible for time-series analysis.

A second difficulty is that contemporary relative energy prices may be a poor indicator of the operating cost expectations of the household. This is a particularly acute problem for appliance decisions made at an earlier date. A thorough analysis of the process of expectation would require the information that is actually available to consumers at the decision point (e.g., historical relative prices up to that point). This data collection task has not been attempted for the WCMS data set; we report below the results of using historical relative price data for households in a single utility service area.

A third, and more fundamental, difficulty in analyzing appliance portfolio choice lies in the question of the interaction of supply and demand. Except for remodeling, choice of space and water heating type is fixed at the date of construction; many newer dwellings also incorporate air conditioning in the construction. Since most dwellings are constructed to stock rather than to order, it would appear that appliance portfolio decisions are largely made by contractors, and that initial prices of houses will adjust to clear existing housing stock. Then, consumer preferences would be detectable primarily in relative profit margins (economic rents) on different housing types rather than in appliance portfolio shares. However, contractors will shift the mix of new housing construction toward types with the highest profit margin. The flow of new housing into the market will then tend to restore equality between profit rates for different housing types by adjusting supply to meet the shares demanded at current "life-cycle" appliance protfolio costs in new construction. If new housing markets are sufficiently responsive to energy price changes and sufficiently large relative to the old housing stock, the overall housing market will be brought into equilibrium, and the analysis of appliance portfolio shares as a function of life-cycle costs (in new construction) will provide information on consumer preferences, independently of contractor's tastes. We shall make this assumption, noting, however, that the period 1970-75 is one of the periods where it is least likely to be true.

Several studies have examined the price sensitivity of appliance saturations. In a cross-section of Standard Metropolitan Statistical Areas for 1960, Wilson (1971) found price elasticities ranging from -2.0 to -5.5 for electric water and space heating appliance shares. Anderson (1973) used state cross-section data for 1969 to estimate the price elasticity of the saturation rate for all-electric homes to be -4.59, and the income elasticity to be 3.72. Baughman and Jaskow (1974) carried out a fuel-choice analysis by appliance type using the 1969 state cross-section data, obtaining elasticities with respect to average electricity price of -2.08 for electric heating marginal share and -1.77 for water heating marginal share.

McFadden (1976) used the Miracle II Survey of 12,000 households conducted in 1975 by San Diego Gas and Electric to fit a binary logit model of the saturation of all-gas (i.e., gas water and space heat) household. The results are given in Table 5. The relative price measure used in this model is defined as

$$\text{(relative cost)} = \frac{\text{(combined gas and electric bill for all-gas household)}}{\text{(combined gas and electric bill for average non-all-gas household)}}$$

The bills are computed using 1975 sample average consumption levels for each fuel type portfolio, and the rate schedules prevailing <u>in the year of construction</u> of the residence. The denominator is a share-weighted average of bills constructed in the manner above for households with electric water heat only, electric space heat only, and electric water and space heat. The elasticity of the share of all-gas households with respect to price is 1.87 at a relative cost of 0.9, and with respect to family income is -0.01 at an income of $14,000 per year.

The analysis of the WCMS data in this study considered eight alternative appliance portfolios, distinguished by the presence or absence of electric water heating, electric space heating, and air conditioning. To simplify the estimation task, the household's air conditioning use was estimated independently of the shares of electric space and water heating.[1] The air conditioning use model has a binary logit form. The results of the estimation are given in Table 6. The elasticity of the share of air conditioned homes with respect to marginal price is -0.166, and with respect to family income is 0.481 at the sample mean income of $12,350.

The water and space heating fuel type model is assumed to have the multinomial logit form $P_{WS} = V_{WS}/(V_{00} + V_{01} + V_{10} + V_{11})$, where $W = 1$ if electric water heat, 0 otherwise; $S = 1$ if electric space heat, 0 otherwise; P_{WS} = share of households with appliance portfolio (W,S); and $\log V_{WS} = \alpha_{WS} + \beta_{WS}$ (income) + γ_{WS} (multiple family + δ_{WS} (relative average cost) + λ_{WS} (if $S = 1$)$\cdot$(heating degree-days) . The normalization $\alpha_{00} = \beta_{00} = \gamma_{00} = \delta_{00} = \lambda_{00} = 0$ is imposed. The relative average cost measure is a ratio of state-wide average cost of electricity to state-wide average cost of gas, for residential customers, in the state in which the subject resides, for 1975.

The results of the estimation are given in Table 7. The elasticities with respect to fuel costs and income are given in Table 8.

Table 8 shows that the impact of increased income is primarily to increase the share of all-electric homes at the expense of homes with electric water heat and non-electric space heat. Since all-electric homes are of recent vintage, while electric water heat only is typical of the oldest housing stock which has been retrofitted with hot water, this result depends critically on the validity of the assumption of equilibrium in the housing market. The impact of increased electricity price is primarily to discourage use of electric water heat and all-electric homes. The share of electric-space-heat-only rises with electricity price — however, this category is small and the elasticity is not reliably estimated.

7. Summary

This study concludes, from the analysis of a national survey of individual households, that average consumption of electricity, conditioned on the availability of air conditioning and on water and space heating fuel type, has an elasticity with respect to faimly income of 0.22, and an elasticity with respect to marginal cost (where marginal costs at different points in the rate schedule are proportional) of approximately -0.25 for households without electric space heat and -0.52 for households with electric space heat. When average cost of electricity rises in proportion to marginal cost, these elasticities increase to approximately -0.33 and -0.60, respectively.

The saturation of air conditioning has an elasticity of -0.17 with respect to marginal price and of 0.48 with respect to income. The elasticities for water and space heating, summarized in Table 8, show in particular a strong negative price elasticity of electric water heat.

These elasticities can be combined to give elasticities of the overall average consumption of electricity, taking into account induced adjustments in appliance portfolios. The overall elasticity of consumption with respect to an explanatory variable z is given by the formula

$$\frac{z}{\bar{K}}\frac{\partial \bar{K}}{\partial z} = \sum_{A=0}^{1}\sum_{W,S=0}^{1} P_A P_{WS}\left\{\frac{K_{WS}}{\bar{K}}\frac{z}{P_A}\frac{\partial P_A}{\partial z} + \frac{z}{P_{WS}}\frac{\partial P_{WS}}{\partial z} + \frac{z}{K_{AWS}}\frac{\partial K_{AWS}}{\partial z}\right\},$$

where

$$\bar{K} = \sum_{A=0}^{1}\sum_{W,S=0}^{1} P_A P_{WS} K_{AWS} \quad ;$$

K_{AWS} equals average consumption of users of type AWS , where $A = 1$ indicates air conditioning, $W = 1$ indicates electric water heat, and $S = 1$ indicates electric space heat; P_A equals saturation of air conditioning (i.e., P_1 = proportion with an air conditioning, P_0 = proportion without); $\bar{K}$ equals average consumption; and the three terms in brackets are the elasticities with respect to z of air conditioning saturations, water and space heating fuel type saturations, and average consumption, respectively. In evaluating the above formula, each elasticity is computed at the relevant means of variables for each type of appliance portfolio.

Table 9 gives the overall elasticities of average consumption with respect to electricity rates, the price of gas, and income. Generally, the elasticities obtained from this study are within, but at the lower end, of the range of long-run elasticities from aggregate studies summarized in Table 1. In particular, a low income elasticity results, primarily from the tendency to substitute other fuels for electricity in water heating as income rises.

Footnotes

1. This paper is based on research carried out by Cambridge Systematics, Inc., for Teknekron, Inc., under a contract from the Federal Energy Administration. The results and conclusions of this paper are solely the responsibility of the authors and have not been reviewed or endorsed by Teknekron, Inc., or the Federal Energy Administration. The authors were assisted in this research by David Brownstone and Robin Kaelber.

2. The source is the Federal Power Commission, Typical Electric Bills, 1975. Typical Electric Bills are population-weighted averages over the rate schedules applying to various segments of utility's customers. This will tend to bias downward the bills attributed to suburban and rural customers who normally face the highest rates. Only bills for general service were collected: this will bias upward the rates attributed to all-electric or electric water-heater homes on preferential rate schedules.

3. A preliminary analysis of the WCMS data suggested that conditioned on cooling degree-days, the use of air conditioning was statistically independent of water and space heating fuel choice. Subsequent analysis has cast doubt

on this conclusion. Hence, a better procedure would be to analyze the three appliance decisions jointly.

References

Acton, J.P., B.M. Mitchell, and R.S. Mowill (1975), "Residential Demand for Electricity in Los Angeles: An Econometric Study of Disaggregated Data," preliminary draft, R-1899-NSF, RAND Corp., Santa Monica, CA

Anderson, K.P. (1973), "Residential Energy Use: An Econometric Analysis," prepared for the National Science Foundation, RAND Corp, Santa Monica, CA

Baughman, M.L. and P.L. Joskow (1974), "Energy Consumption and Fuel Choice by Residential and Commercial Consumers in the United States," M.I.T., Cambridge, MA

Electric Utility Rate Design Study (1977), "Considerations of the Price Elasticity of Demand for Electricity," (Topic 2), prepared by the National Economic Research Associates for the Electric Power Research Institute, Palo Alto, CA

Federal Energy Administration (1976), 1976 National Energy Outlook, Federal Energy Administration, Wasington, DC

Fisher, F. and C. Kaysen (1962), A Study in Econometrics: The Demand for Electricity in the United States, North-Holland, Amsterdam

Halvorsen, R. (1976), "Demand for Electric Energy in the United States," Southern Economic Journal, Vol. 18, No. 2

Houthhakker, H.S. and L. Taylor (1970), Consumer Demand in the United States, second edition, Harvard University Press, Cambridge, MA

Lacy, A.W. and D.R. Street (1975), "A Single Firm Analysis of the Residential Demand for Electricity," Department of Economics, Auburn University

Lyman, R.A. (1974), "Price Elasticities in the Electric Power Industry," Department of Economics, University of Arizona (draft: not for quotation)

McFadden, D., C. Puig, and D. Kirshner (1977), "A Simulation Model for Electricity Demand," Final Report, Cambridge Systematics, Inc., Berkeley, CA

McFadden, D. (1976), "Forecasting the Impacts of Alternative Electricity Rate Structures: A Feasibility Study," Final Report to the California State Energy Resources Conservation and Development Commission, Contract 4-0134, Sacramento, CA

McFadden, D. and C. Puig (1975), "An Econometric Model of the Demand for Electricity," Ch. 2 in Teknekron, Inc., "Economic Impact of Water Pollution Control on the Steam Electric Industry," Report EEED-12, Berkeley, CA

Mount, T.D., L.D. Chapman, and T.J. Tyrrell (1973), "Electricity Demand in the United States: An Econometric Analysis," Oak Ridge National Laboratory, Oak Ridge, TN

Newman, D.K. and D. Day (1975), The American Energy Consumer, Ballinger

Rao, C.R. (1973), Linear Statistical Inference and Its Applications, Wiley, New York

Taylor, L.D. (1975), "The Demand for Electricity: A Survey," Bell Journal of Economics and Management Science

Taylor, L.D. (1975a), "The Demand for Energy: A Survey of Price and Income Elasticities," National Academy of Science Committee on Nuclear and Alternative Energy Systems, Washington, DC

Taylor, L.D., G. Blattenberger, and P. Verleger (1976), "Residential Demand for Energy," Report to the Electric Power Research Institute (preliminary draft), Department of Economics, University of Arizona, Tucson, AZ

Uri, N.D. (1975), "A Dynamic Demand Analysis for Electrical Energy by Class of Consumer," Working Paper No. 34, Bureau of Labor Statistics, U.S. Government Printing Office, Washington, DC

Wilder, R.P. and J.F. Willenborg (1975), "Residential Demand for Electricity: A Consumer Panel Approach," Southern Economic Journal, Vol. 42, No. 2

Wilson, J. (1971), "Residential Demand for Electricity," The Quarterly Review of Economics and Business