ELECTRICITY CONSUMPTION BY TIME OF USE IN A HYBRID DEMAND SYSTEM

PREPARED FOR THE LOS ANGELES DEPARTMENT OF WATER AND POWER
AND THE JOHN A. HARTFORD FOUNDATION

BRIDGER M. MITCHELL AND JAN PAUL ACTON

R-2628-DWP/HF
DECEMBER 1980

Rand
SANTA MONICA, CA. 90406

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PREFACE

The Los Angeles Electricity Rate Study--a five-year project concluded in 1980--was designed to yield information about the effects of alternative pricing structures for residential consumers. The experimental plans included time-of-day, seasonal, and time-invariant rates for approximately 1800 households over a 30-month period. The study was conducted jointly by the Los Angeles Department of Water and Power and The Rand Corporation, with partial funding from the U.S. Department of Energy.

This report presents results of behavior under the time-of-use plans, especially those which charge a different price for electricity at certain hours, five or seven days per week. Such time-of-use rates are being actively considered in most regulatory jurisdictions, but there is considerable uncertainty about their effects among residential users. Since the Los Angeles experiment was designed to yield demand curve estimates, results of this study should be useful in forecasting likely effects in a number of different service territories.

In the study, the authors develop models that separate the effects of prices, demographic factors, appliances, and weather on electricity consumption. The models support analysis of electricity use in varied circumstances and permit forecasting consumption under new rate structures. The report should be of particular interest to electric utilities and regulatory bodies investigating consumer responses to electricity prices. For economists and policy analysts it provides an analytic framework for evaluating and forecasting the effects of time-of-use pricing that incorporates a system of time-of-use demand equations.

Related Rand research on electricity pricing and demand can be found in the following publications:

- *Design of the Los Angeles Peak-Load Pricing Experiment for Electricity*, Willard G. Manning, Jr., Bridger M. Mitchell, and Jan Paul Acton, R-1955-DWP, November 1976.

- *Lessons To Be Learned from the Los Angeles Rate Experiment in Electricity*, Jan Paul Acton, Willard G. Manning, Jr., and Bridger M. Mitchell, R-2113-DWP, July 1978.
- *Peak-Load Pricing: European Lessons for U.S. Energy Policy*, Bridger M. Mitchell, Willard G. Manning, Jr., and Jan Paul Acton, Ballinger Publishing Company, 1978.
- *The Los Angeles Senior Citizen Lifeline Electricity Rate*, Timothy J. Sullivan, R-2278-DWP/NSF, January 1979.
- *Sample Selection in the Los Angeles Electricity Rate Study*, Winston K. Chow and Bridger M. Mitchell, R-2430-DWP, July 1979.
- *Conducting a Survey Using the Client's Staff: Evaluation of Interviewer Performance in the Electricity Rate Study*, Sandra H. Berry, R-2223-DWP, September 1979.
- *Evaluating Time-of-Day Electricity Rates for Residential Customers*, Jan Paul Acton and Bridger M. Mitchell, R-2509-DWP, November 1979.
- *Do Time-of-Use Rates Change Load Curves?*, Jan Paul Acton and Bridger M. Mitchell, R-2588-DWP/EPRI, May 1980.
- *The Effect of Time-of-Use Rates in the Los Angeles Electricity Study*, Bridger M. Mitchell and Jan Paul Acton, N-1533-DWP/HF, October 1980.
- *Planning, Processing, and Analyzing Data for Residential Load Studies*, Jan Paul Acton and Bridger M. Mitchell, N-1534-DWP, June 1980.
- *Seasonal Electricity Demand and Pricing Analysis with a Variable Response Model*, Lee A. Lillard and Jan Paul Acton, R-2425-DWP, May 1980.
- *Residential Electricity Demand Under Time-of-Day Pricing: Exploratory Data Analysis from the Los Angeles Rate Study*, Willard G. Manning, Jr., and Jan Paul Acton, R-2426-DWP/HF, December 1980.

SUMMARY

Time-of-use (TOU) electricity rates have been widely used in Europe for several decades to reflect peak-load cost variations. Such rates have recently been tested in the United States by a number of utilities, and several of those studies were designed to yield detailed data on electricity consumption under a variety of experimental rates and different levels of major variables affecting electricity use--household appliances, economic and demographic characteristics, and weather conditions.

The TOU rate experiments offer a wealth of potential information but present the analyst with a choice of methods: On the one hand, the principal effects can be determined through relatively simple single equation estimates that impose a minimum of restrictions. Such estimation techniques impose a minimum of structure, but they fail to exploit the implications of utility maximizing behavior from neoclassical demand theory and cannot calculate changes in consumer surplus, which require estimated demand curves. At the other extreme, highly structured systems of demand equations can be estimated in order to extract more information from the experimental data. However, these systems require highly restrictive or untestable assumptions that increase the risk of obtaining spurious empirical findings.

The Los Angeles Electricity Rate Study included 931 households on one of 17 TOU rate plans and an additional 337 households on seasonal, flat or declining block rate plans which had their electricity use recorded continuously. Peak and off-peak rates of different levels and duration applied during four three-hour rate periods plus a 12-hour overnight period.

To estimate TOU rate effects, we develop a hybrid demand system approach, first estimating the basic pattern of demand with a minimum of restrictions and then imposing greater structure after the basic pattern of response has been determined. This approach allows us to separate the effects of weather, appliance holdings, and other explanatory factors from the effects of price and provides flexibility in applying the estimates to another forecasting situation where exogenous estimates of nonprice demand can be easily incorporated.

Our basic model of electricity consumption by time of use may be schematically represented by three types of systematic components plus unmeasured factors (random error):

$$\text{electricity}_{hjt} = f\ (\text{weather}_{hjt},\ \text{household}_{hj},\ \text{price}_{hj},\ \text{error}_{hjt}).$$

Consumption in kilowatt hours at hour h, by household j, in month t depends on the weather; on that household's characteristics in terms of electrical appliances, behavioral patterns, and economic resources; and on the prices by time of use charged for electricity.

The hybrid model involves a three-stage approach. First, we estimate the variation in consumption in each rate period that results from the month-to-month variation in weather and adjust each household's consumption to a level corresponding to average weather conditions. Second, we determine how the adjusted consumption in each rate period, including the mean weather effects, is affected by prices and household characteristics. Finally, we explain the level of total electricity consumption by the household's characteristics and the average price of electricity in peak and off-peak hours.

Weather-sensitive consumption depends on the presence of electric air conditioning and space heating appliances and on temperature. The estimated equations for each rate period account for 18 to 53 percent of the monthly variation in consumption and provide the basis for adjusting each household's consumption to an estimated level in each rate period at average temperatures. To analyze the effects of TOU rates on weather-adjusted consumption by rate period we first estimate an analysis of covariance model in which the effect of each of the 17 TOU rate plans is represented by a separate set of coefficients. We find systematically that the percentage share of total electricity consumption used in each period of time is negatively related to the price faced in that period. Furthermore, the greatest effects on the percentage share are due to introducing a peak/off-peak price differential; increasing the difference between peak and off peak prices further reduces shares in peak periods, but not in proportion to the price increase. Based on these results we formulate a system of demand equations and estimate its complete set of parameters. These equations simultanuously explain both the distribution of consumption by rate period and the overall level of consumption as a function of all TOU prices.

TOU rates not only change the distribution of electricity consumption by period of the day, they also affect the total quantity of electricity. After creating a price index to reflect the average costliness of electricity under a TOU rate, we find that the price elasticity of total consumption is about -.13 at an average price of 3.5¢ per kwh and about -.19 of an average price of 5¢ per kwh.

In addition to these price effects, the effects of appliance variables, demographics, and weather each have estimated coefficients of the expected sign and magnitudes that correspond well with exogenous estimates--for example, estimates from end use studies of appliance-specific usage.

The full effect of a TOU rate is revealed in the change in both the percentage share of electricity consumed in a given time period and in total electricity consumption. The resulting price elasticity is a "full, uncompensted price elasticity" that includes the changes in total expenditure on electricity and change in real income that result from a change in the price in a particular time period. We report these full price elasticities at a reference price at 5¢ per kwh for households having a variety of assumed appliance holdings. For households with relatively few appliances, own price elasticities range from -.05 to -.13. For households with both a swimming pool and air conditioning, the own price elasticities range from -.13 to -.32. Cross-elasticity estimates show that most of the load shifting induced by TOU rates is due to households with pools or air conditioners.

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We gratefully acknowledge the support of the Los Angeles Department of Water and Power and especially Michael T. Moore, the original project officer. A grant from the John A. Hartford Foundation is permitting us to extend this analysis into a more national focus.

CONTENTS

PREFACE iii

SUMMARY v

ACKNOWLEDGMENTS ix

Section

I. INTRODUCTION 1

II. THE LOS ANGELES EXPERIMENT AND DATA BASE 4
    Design of the TOU Experiment 4

III. OVERVIEW OF THE ANALYTIC APPROACH 8
    The Hybrid Model of Demand 8
    Unit of Analysis 10

IV. EMPIRICAL RESULTS 13
    Weather-Sensitive Consumption 13
    Time-of-Use and Total Consumption in an Analysis of Covariance Framework 16
    Demand System Analysis 24
    Miscellaneous Results 33

V. TOU DEMAND ELASTICITIES 35
    Price Elasticities of Demand 35
    Comparison with Other TOU Price Elasticity Estimates .. 39
    An Illustrative TOU Rate 40

REFERENCES 43

I. INTRODUCTION

Peak-load pricing has long been advocated for the sale of electricity and other services in which periodic variations in demand are jointly supplied by a common plant of fixed capacity. Time-of-use (TOU) electricity rates have been widely used in Europe for several decades to reflect peak-load cost variations. By contrast, in the United States TOU rates began to receive serious consideration only following the 1973-74 Arab oil embargo.[1]

To better understand the likely consequences of TOU pricing for residential users, several U.S. electric utilities undertook a series of rate trials beginning in 1975.[2] Most of these "demonstration projects" had very limited variation in experimental prices and did not permit own- and cross-price effects of a TOU rate to be determined. However the more ambitious studies were designed to yield detailed data on electricity consumption under a variety of experimental rates and different levels of major variables affecting electricity use--household appliances, economic and demographic characteristics, and weather conditions.

Several analytic approaches are available to estimate the own- and cross-price effects of TOU rates in order to forecast changes in electricity use and measure net welfare effects.[3] The principal effects can be determined from an analysis of variance or covariance of independently estimated equations for each rate period. Such estimation techniques impose a minimum of structure, but they fail to exploit the implications of utility maximizing behavior from

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[1] See Mitchell, Manning and Acton (1978) for a review of European pricing and Joskow (1977) for a history of recent U.S. pricing.

[2] In all, about 15 "rate demonstrations" were undertaken with the encouragement and partial support of the Federal Energy Administration (and later the Department of Energy). Their principal features are reviewed in Hill et al. (1979) and Aigner and Poirier (1980).

[3] Typically, conventional meters cost $20 plus installation while TOU meters presently cost $100 to $150 plus installation. Thus, introducing TOU rates raises an important benefit/cost question for smaller residential users.

neoclassical demand theory and cannot calculate changes in consumer surplus, which require estimated demand curves. At the other extreme, highly structured systems of demand equations can be estimated in order to extract more information from the experimental data. Such systems impose restrictions on the demands for electricity across different rate periods and frequently between electricity and other goods as well.[1] However, these systems require highly restrictive or untestable assumptions that increase the risk of obtaining spurious empirical findings.[2]

Another limitation of neoclassical consumer theory is its lack of guidance regarding the effects of weather, appliance ownership, and a number of household characteristics on electricity demand. Indeed, in many specifications the dependent variable becomes "weather-adjusted consumption" or "relative demand per electrical appliance;" under these conditions, there is no compelling reason to expect Slutsky symmetry, homothetic separability, or other features of demand system theory to hold.

To reliably estimate TOU rate effects we proceed cautiously and employ a hybrid approach to modeling and estimating TOU electricity demand. First, we estimate the basic pattern of demand with minimal restrictions to see if consumer behavior is broadly consistent with economic theory. Then, we incorporate greater structure and restrictions after the basic pattern of response has been determined. This staged approach offers the advantage of being able to test some simple implications of rational behavior--for example, greater consumption under more extreme weather conditions and reduced consumption in the face of higher overall prices--before the consumer's response is represented by a large number of parameters which require simultaneous interpretation. Furthermore, this approach allows us to assess whether the estimated components of the demand estimates--for example, the predicted use by different types of appliances--are reasonable when compared to information from other sources such as end-use measurements. The hybrid approach also allows us to separate the effects of weather, appliance holdings, and other

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[1] See Aigner and Poirier (1980) for a general review of demand systems available for estimating TOU electricity consumption and a critique of their application in a number of TOU studies.

[2] For example, using Monte Carlo techniques Kohler (1980) demonstrated that estimates using an indirect translog utility function with homotheticity imposed can yield "significant" price response coefficients even when none are present in the actual data.

explanatory factors from the effects of prices. This permits greater flexibility in applying the estimates to another forecasting situation where exogenous estimates of non-price demand can be easily incorporated.

In the remainder of this report we develop the model for estimating electricity demand under TOU pricing and apply it to data from the Los Angeles Electricity Rate Study. The next section presents a brief description of that study and its data base. Section III outlines the hybrid modeling approach and some of its advantages. Section IV presents the empirical results. Finally, Section V summarizes the results in terms of demand elasticities and compares them with estimates obtained from other studies.

II. THE LOS ANGELES EXPERIMENT AND DATA BASE

The Los Angeles Electricity Rate Study, jointly undertaken by the Los Angeles Department of Water and Power and The Rand Corporation over the 1975-1980 period, included extensive variation in rate forms and rate levels so that statistically identified own- and cross-price effects could be determined over a wide variety of costing and demand conditions. The study had two major components--a seasonal experiment, in which the price was constant throughout the day but varied between winter and summer, and a time-of-use experiment, in which rates varied over 3-hour rating periods.[1] The present analysis treats only TOU demand.[2]

DESIGN OF THE TOU EXPERIMENT

In all, 1268 households were available for time-of-use analysis. Nine hundred and thirty one households were observed on one of 17 TOU rates that apply either 5 or 7 days per week (for a total of 34 different rate structures). An additional 337 households faced either seasonal, flat, or declining-block rates but had their use recorded continuously; they served as "control" households for time-of-use customers, and their consumption could be included in much of the analysis. Magnetic tape cassette meters recorded the electricity use every 15 minutes for these 1268 households.

Table 1 shows the distribution of experimental households by rate plans. Five congruent rate periods (09-12, 12-15, 15-18, 18-21, 21-09) permit data from the 17 TOU rate plans to be analyzed simultaneously in a single demand system.

Participation in the study was voluntary. Households were first interviewed to determine basic household demographics and appliance ownership. If they were eligible for the study (i.e., paid their own electricity bill,

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[1] Optimal experimental design followed procedures developed by Conlisk and Watts (1969), and individuals were assigned to particular procedures developed by Morris (1979). See Acton, Mitchell, and Manning (1977) for an overview of the study and its policy objectives; Manning, Mitchell, and Acton (1979) for a description of the statistical design; and Chow and Mitchell (1979) for a description of the sampling procedures.

[2] See Lillard and Acton (1980) for an analysis of seasonal demand.

Table 1

RATE PLANS AND NUMBER OF HOUSEHOLDS

	Peak Period		Prices per kWh (cents)			Number of Households on Peak Rates	
No.	i	Hours	Peak	Off-Peak	Average	Mon.-Fri.	Mon.-Sun.
00	--	00-24	Conventional Declining Block Rate		--	--	175[c]
0S	--	00-24	Seasonal[b]		--	--	68[c]
0A	--	00-24	2	2	2	--	56[c]
0B	--	00-24	5	5	5	--	38[c]
1	1	09-12	5	2	2.35	37	34
2	1	09-12	9	2	2.81	24	27
3	1	09-12	13	2	3.27	9	9
4	2	12-15	9	2	2.87	18	16
5	2	12-15	13	2	3.36	10	10
6	3	15-18	5	2	2.43	9	9
7	3	15-18	9	2	3.01	34	35
8	3	15-18	13	2	3.59	29	39
9	4	18-21	5	2	2.55	9	10
10	4	18-21	9	2	3.29	27	26
11	4	18-21	13	2	4.03	26	25
12	5	21-09	5	2	3.30	72	71
13	3-4	15-21	7	2	3.34	16	15
14	2-4	12-21	5	2	3.36	49	56
15	2-4	12-21	9	2	5.17	27	27
16	1-4	09-21	5	1	3.27	27	30
17	1-4	09-21	9	1	5.54	35	34
TOTALS						458	810

[a] Average price per kWh computed for the reference load curve at a flat rate.

[b] Households with seasonal plans and cassette meters are used in the share analysis but not in the total consumption analysis.

[c] Households with recording meters.

no family member worked for Rand or the Los Angeles Department of Water and Power, etc.), they received an offer to join the study and pay for electricity under an experimental rate. Our desire to estimate demand curves that might apply in future circumstances led to plans under which some households could have been worse off if their electricity remained unchanged. Those households were offered quarterly compensation in the form of "participation payments" based on their preexperimental level of use; the payments were unaffected by experimental use. Although self-selection bias is an appropriate concern in such voluntary experiments, over 92 percent of the eligible households offered an experimental rate plan accepted it, and we make no adjustment in the results reported below.[1]

Household Information

Extensive household-specific information was collected in three surveys made at the beginning, the midpoint, and the end of the study. Data on household composition, appliance ownership, income, and attitudes were collected during each 30-minute interview. In the present analysis, we use the responses provided in the first two surveys, which apply most directly to the 24-month period of data used for the empirical analysis. Household values for income, family size, and housing rental value are updated from the end-project survey.

Weather Data

Hourly weather data are collected in each of three climate zones in the city of Los Angeles: (1) a mild coastal zone with moderate summer and winter temperatures, (2) an inland valley zone with more extreme temperatures in both summer and winter, and (3) a civic center area with intermediate temperatures. We reflect weather through heating and cooling degree hours, taken as deviations from $65^{o}F$.[2] This use of hourly measures of temperature

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[1] In exploratory data analysis using the first 18 months of experimental data, Manning and Acton (1980) found that making a correction for selection bias reduced own-price elasticities in evening and nighttime consumption periods by a few percentage points.

[2] Cooling-degree hours (CDH) = $\max(T^{o}F - 65^{o}, 0)$; heating-degree hours (HDH) = $\max(65^{o} - T^{o}F, 0)$. Both are averaged over the month in the relevant rate period.

captures the detailed variation in weather over a day. In contrast, the more familiar heating or cooling degree-day--which is based on mean daily temperature--takes on a single value in a 24-hour period, which masks the differences between two days with identical mean temperature but very different high and low temperatures.

III. OVERVIEW OF THE ANALYTIC APPROACH

Our basic model of electricity consumption by time of use may be schematically represented by three types of systematic components plus unmeasured factors (random error):

$$\left(\text{electricity}_{hjt}\right) = f\left(\text{weather}_{hjt}, \text{household}_{hj}, \text{price}_{hj}, \text{error}_{hjt}\right). \quad (1)$$

Consumption in kilowatt hours at hour h, by household j, in month t depends on the weather; on that household's characteristics in terms of electrical appliances, behavioral patterns, and economic resources; and on the prices by time of use charged for electricity.

The primary objective of a TOU electricity pricing experiment is to accurately measure the price component of electricity consumption so that the changes in load resulting from proposed TOU rates can be estimated and the economic benefits of such pricing evaluated. To do so, however, the weather and the household-specific components of consumption must be accurately accounted for.

THE HYBRID MODEL OF DEMAND

In this report we adopt a three-stage approach. First, we estimate the variation in hourly consumption that results from the month-to-month variation in weather and adjust each household's consumption to a level corresponding to average weather conditions. Second, we determine how the adjusted consumption, including the mean weather effects, is distributed over the hours of the day. Because hourly consumption data were not measured prior to the introduction of TOU rates in the Los Angeles experiment, it is necessary to separate the "permanent" or normal use in each time period from the response to TOU rates. To accomplish this we estimate a reference load curve (for a household of given characteristics at average weather) that indicates the proportions of daily electricity consumption used in each period of the day when a uniform price for electricity is charged at all hours. The experimental TOU rates are then used to explain deviations from this load curve. Finally, in the third stage of analysis, we explain the level of total electricity consumption by the household's characteristics and the average price of electricity in peak and off-peak hours.

Two Analytic Approaches

We report estimates of the price-component effects based on two types of analysis. A straightforward approach to assessing TOU rates is to first standardize all households to a common reference load curve and then to measure separately, for each of the 17 weekday TOU rates in the Los Angeles experiment, the effect of each rate on (1) consumption in each period of the day and (2) total consumption. This *analysis of covariance* method imposes a minimum number of assumptions when processing the original data and reveals the basic patterns of response produced by the experiment. It amounts to assuming that the responses to the TOU rates of the 17 groups of households have nothing in common.

In fact, the empirical results suggest common regularities among the different groups that are consistent with the theory of consumer demand. We therefore introduce a two-level *demand system* and estimate its complete set of parameters. The demand system equations simultaneously explain both the distribution of consumption by rate period and the overall level of consumption as a function of all TOU prices. These estimates yield own-price and cross-price effects on demand for five weekday rate periods and permit prediction of load shifts due to proposed TOU rate plans, including rates not directly tested in the experiment. The estimated coefficients measure the change in relative loads. Full price elasticities calculated from these coefficients permit comparison with estimates from other models and data sources, and the estimated load curve shows the overall effect of a representative TOU tariff.

Advantages of Hybrid Model

The hybrid model allows estimation with minimal structure imposed on the data before proceeding with more restrictive analysis. The decomposition of demand into a weather component, a demographic and appliance component, and a behavioral response to TOU prices permits greater flexibility and forecasting accuracy when analyzing TOU effects under different circumstances.

Using a weather-adjusted reference load curve removes one important source of variation for which economic theory offers little guidance. The price-related and household-specific estimates are more useful for forecasting loads that have had weather effects removed. In applying these experimental results to another utility service area, the analyst can either use a predicted reference load curve (based on the weather component estimated with L.A. data) or a local reference load curve (perhaps based on a load study) which may more accurately represent local weather-related effects.

Second, by separating relative consumption by time-of-use from total electricity consumption, exogenous estimates or assumptions of long-run effects that may be unmeasurable in an experimental context can be introduced. For example, if the analyst thinks secular trends or price-induced changes in appliance ownership will produce a shift in total consumption, he can combine that information with the estimates that capture the behavioral shifts by the time of use conditional on a given stock of appliances. In addition, if it is anticipated that future appliances may contain features that assist adaptation to TOU rates (e.g., built-in timers), the coefficients on those appliances can be adjusted within the model's equations to account for those effects.

UNIT OF ANALYSIS

The household is the unit for present analysis. Consumption data for each household are available for each 15-minute interval over the 30 months of its participation in the experiment (which covered the period July 1976-June 1979--approximately 100 million observations). The data available to explain electricity use are of two basic types: time-dependent variables, chiefly measures of weather conditions, but also the occurrence of vacations and changes in household appliances and demographic factors; and household-dependent variables, which are effectively constant over the life of the experiment. Household-dependent variables are the price of electricity by time of day and the household's appliances, demographic, and economic characteristics.[1]

As a practical matter, such voluminous data require aggregation prior to analysis. For this report we have used 24 months of data from January 1977 to December 1978, a period during which nearly all households faced only their experimental rates. We aggregated the raw 15-minute observations in each period, K_{hjt}, into the average daily consumption in each rate period for each month. Using the 10 rate periods in Table 2 our initial data unit is the kilowatt-hour measure

$$\tilde{X}_{ijt} = \frac{1}{n_{hjt}} \sum_{h \varepsilon H(i)} K_{hjt} \qquad (2)$$

where h is the index of 15-minute intervals

H(i) is the set of 15-minute intervals in rate period i

j indexes the household

t indexes the month

n_{ijt} is the number of effective 24-hour days of observations per month[2]

Note that the daytime periods 1 to 4 and 6 to 9 are each 3 hours long; however, the overnight periods, 5 and 10, are each 12 hours long because there is no price variation within these overnight periods. Unless stated otherwise, all analysis in this report refers to average daily consumption in each period.

This level of data aggregation strikes a balance between the detail needed to detect the effects of specific rate plans and the costs of

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[1] Household demographic and economic variables--family size, income, housing value, and the like--can change during the study. We employ average values of these variables to explain permanent level of use. Appliance holdings can also change during the study. In the monthly weather regressions, these variables change monthly. In the remainder of the analysis, the dependent variable is a measure of average consumption and an average value of each appliance is used.

[2] Missing observations occur because of blackouts, meter failures, magnetic tape defects, and the like. Calculating the mean consumption per period by dividing by the actual number of observations corrects for the missing data.

Table 2

TIME OF USE RATE PERIODS

Hours	Weekday	Weekend
09-12	1	6
12-15	2	7
15-18	3	8
18-21	4	9
21-09	5	10

processing daily or hourly observations.[1] For particular questions of special interest, subsequent analysis might use less aggregated data--for example, hourly loads for selected days of the year.

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[1] Two alternatives to the data aggregation employed here were illustrated in analysis of the Connecticut rate study. Hendricks, Koenker, and Poirier (1977) fit a smooth periodic function (a cubic spline) to the hourly data over a week. They can explain the parameters of this function in terms of household demographics, price, etc. At the other extreme, Granger et al. (1977) estimate hourly regressions with no aggregation of the data.

IV. EMPIRICAL RESULTS

In the hybrid model of demand, we first estimate the weather component of electricity use and adjust each household's consumption to a level corresponding to that at average weather. The weather-adjusted data determine a reference load curve for each household. The effects of household characteristics and TOU rate plans on electricity use by time of day and on total consumption are estimated as deviations from this load curve. In this section we present model-free estimates of demand based on an analysis of covariance and then present estimates of total demand for electricity and its distribution by time period using a complete system of demand equations. Finally, we report some miscellaneous empirical results of electricity use under experimental circumstances.

WEATHER-SENSITIVE CONSUMPTION

The primary cause of month-to-month variation in electricity consumption that is measurable with available explanatory variables is weather. Temperature differences cause electricity use to vary by time of day, and this variation is largely independent of the price of electricity. For households whose price of electricity does not vary over the hours of the day, we assume that consumption $\tilde{X}_{ijt}$ in period i can be decomposed into a weather component, $W_i(\cdot)$, plus a component for household j that is invariant to weather conditions, a_{ij}.

To estimate each weather component, we follow work reported earlier and assume that the effective stock of weather-sensitive appliances varies with their capacity, the area to be cooled or heated, and outside temperature.[2] The air conditioning variable (AC) is an index that combines central, wall, and evaporative units weighted by their relative consumption rates and house size. The variable (HEAT) measures the

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[1] In addition to temperature, humidity and the amount of natural illumination alter electricity use. These secondary factors are not incorporated into the estimates presented here except to the extent that they vary systematically by weather zone.

[2] See Acton, Mitchell, Sohlberg (1980).

availability of space heating and house size.[1] The heating and cooling appliances are affected quadratically by the monthly mean temperature (TEMP) in each rate period, measured in cooling degree-hours for air-conditioning and in heating-degree hours for space heating. Hourly temperature readings are available for three distinct climatic zones in Los Angeles, but not at each residence; the degree-hour variable for a household is that measured for its zone in the city. The other time-dependent variables that influence monthly consumption are whether a member of the household is normally at home during the period (HOME) or is on vacation in that month (VAC).[2]

Ten weather equations, one for each rate period, take the following general form

$$\tilde{X}_{ijt} = a_{ij} + W_i(AC_{jt}, HEAT_{jt}, TEMP_{ijt}, VAC_{jt}, HOME_{jt}) + e_{ijt}. \qquad (3)$$

$i = 1,\ldots,10$ (rate period)

$j = 1,\ldots,n$ (household)

$t = 1,\ldots,T$ (month)

The detailed specification is shown in Table 3.

The weather equations are estimated using 24 months of data from the 337 households on flat, seasonal, and declining-block rates. For computational convenience, the parameters are estimated using deviation from household means as observations. Ordinary least squares estimates, assuming the unobserved error e_{ijt} to be independently distributed with constant variance, explain 18 to 53 percent of the variation in mean monthly weekday and weekend consumption by rate period.

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[1] Because only 6 percent of the experimental households reported any form of electric space heating no attempt was made to distinguish different types of heating units.

[2] Our fixed-coefficient model assumes that the same weather component W_i applies to all households facing the same temperature and having similar heating and cooling equipment. Considering the coefficients as random variables allows an alternative specification that would permit the weather-sensitive consumption to vary by household. For an application of this approach in the context of seasonal electricity pricing see Lillard and Acton (1980).

Table 3

SPECIFICATION OF WEATHER-SENSITIVE CONSUMPTION EQUATIONS[a]

$$\begin{aligned}\tilde{X}_{ijt} = a_{ij} &+ \beta_{1i}\, AC_{jt}\cdot CDH_{ijt} + \beta_{2i}\, AC_{jt}\cdot CDH^{2}_{ijt} \\ &+ \gamma_{1i}\, HEAT_{jt}\cdot HDH_{ijt} + \gamma_{2i}\, HEAT_{jt}\cdot HDH^{2}_{ijt} \\ &+ \delta_{i}\, VAC_{jt} + \rho_{i}\, HOME_{jt} \\ &+ e_{ijt}\end{aligned}$$

$i = 1,\ldots,10$ (rate periods)
$j = 1,\ldots,\ n$ (households)
$t = 1,\ldots,\ T$ (months)

Definition of Variables:

$AC_j = [1 + \ell n(ROOMS_j/\overline{ROOMS})] \cdot ACSTOCK_{jt}$

$$\begin{aligned} ACSTOCK = &\ \ 1 \cdot \text{central electricity or combination gas/electric A/C} \\ &+.60 \cdot \text{central gas A/C} \\ &+.37 \cdot \text{central evaporative A/C} \\ &+.18 \cdot \text{number of wall refrigerative A/C} \\ &+.12 \cdot \text{number of wall evaporative A/C}\end{aligned}$$

$HEAT_{jt} = [1 + \ell n(ROOMS_j/\overline{ROOMS})] \cdot HEATSTOCK_j$

$$\begin{aligned} HEATSTOCK = &\ \ 1 \cdot \text{heat pump} \\ &+1 \cdot \text{central electric space heat} \\ &+1 \cdot \text{central combination gas/electric space heat}\end{aligned}$$

VAC_{jt} = number of days household j was empty in month t.

$HOME_{jt}$ = 1 if household usually at home daytime on weekdays or on weekends.

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[a] Equation estimated by OLS with all variables as deviations from household-specific means; e.g. $(\tilde{X}_{ijt} - \frac{1}{T}\sum\tilde{X}_{ijt})$ where T_j is the number of months of data available for household j. Total observations = 7,024.

The weather component W_i is the mean consumption of electricity used for cooling or heating at a given outside temperature. Table 4 shows that when the temperature in the morning is 80°F, households with central air-conditioning use an average of .75 kWh per hour for space cooling. This value falls at midday and then rises substantially in the afternoon and evening periods. The variation in mean rates of consumption undoubtedly reflects the increased probability that the home is occupied in the later hours of the day and also, perhaps, the increased energy required to cool unoccupied rooms that have heated up by late afternoon.

For space heating, the weather component of mean consumption at 55°F on weekdays is relatively constant. (The projected negative consumption during the warmest period of the day is beyond the range of average temperatures at those hours.) This regularity, and the lower mean rate of consumption in the overnight period, is consistent with a constant daytime thermostat setting that is set back to a cooler level overnight. Because electric space heating is not widely used in Los Angeles these estimates are somewhat less reliable than those for air-conditioning.

TIME-OF-USE AND TOTAL CONSUMPTION IN AN ANALYSIS OF COVARIANCE FRAMEWORK

To put all households on a comparable basis we use the estimated weather components to adjust each household's electricity use to the estimated level that would prevail if temperatures were at the city-wide average levels $\overline{TEMP}_i$ in the ith rate period:

$$X^{adj}_{ijt} = \tilde{X}_{ijt} - W_i(AC_{jt},\ HEAT_{jt},\ TEMP_{ijt} - \overline{TEMP}_i,\ VAC_{jt},\ HOME_{jt}) \qquad (4)$$

These adjusted consumption values, which fluctuate monthly due to unmeasured random effects, are averaged over 24 months for each household

$$\alpha_{ij} = \frac{1}{T} \sum_t X^{adj}_{ijt} \qquad (5)$$

to obtain the household-specific component of electricity consumption at each rate period. The components α_{ij} incorporate the jth household's pattern of consumption that is due to its appliance and

Table 4

WEATHER-SENSITIVE CONSUMPTION: HOUSEHOLDS WITH CENTRAL AIR CONDITIONING AND ELECTRIC SPACE HEATING

Period		Mean Weekday Consumption (kWh/hr)	
i	hours	Cooling (at 80°F)	Heating (at 55°F)
1	09-12	.75	1.48
2	12-15	.23	-.32[a]
3	15-18	1.01	1.33
4	18-21	2.33	1.08
5	21-09	.30	.46

[a] Temperature is outside range of average monthly data at midday.

demographic characteristics, its estimated consumption at average weather conditions, and its responses to its rate plan. Because all of the major time-dependent explanatory variables have been incorporated into the estimated weather component, the remaining analysis is conducted using average 24-month consumption values and explanatory variables that are essentially constant for each household j.

kWh Share Equations

We are now in a position to analyze the distribution of household j's consumption by time of day in terms of its relative load curve. For the five weekday rate periods in the experiment, this load curve is given by the household's weekday consumption component α_{ij} in each period divided by its total daily consumption or

$$s_{ij} = \frac{\alpha_{ij}}{\alpha_j}, \; i = 1 \ldots 5 \text{ and } \alpha_j = \sum_1^5 \alpha_{ij}. \qquad (6)$$

These consumption shares s_{ij} vary systematically with household characteristics; they are also changed by TOU rates.[1]

We estimate share equations for each of the five rate periods of the form

$$\begin{aligned} s_{ij} &= f(\text{PLAN}_j, \text{APPL}_j, \text{DEMO}_j) + e_{ij} \\ &= a_i + \sum_m b_{im} \text{ PLAN}_{mj} + \sum_k f_{ik} \text{ APPL}_{kj} + \sum_k g_{ik} \text{ DEMO}_{kj} \qquad (7) \\ i &= 1, \ldots, 5 \end{aligned}$$

The vector of dummy variables (PLAN_m) indicates which rate plan is assigned to the household, and vectors of appliance (APPL_k) and demographic (DEMO_k) variables allow us to standardize relative loads across households with different characteristics. These equations are estimated by ordinary least squares with the same set of explanatory variables in

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[1] For expository convenience we refer to weekday loads and shares. A similar analysis is carried out for weekend consumption.

each equation, ensuring that the sum of the estimated shares is 100 percent for each household. They explain 24 to 36 percent of the variations in mean weekday relative loads.

The plan, appliance, and demographic variables are all important determinants of the household load curve. For economy of exposition, we report only the plan effects from the analysis of covariance and discuss the demographic and appliance variables later in the context of the demand system model.

TOU Price Effects on Relative Loads

In the share equations (7) the effect of prices is represented by separate dummy variables $PLAN_m$ for each type of plan.[1] For households on the "2¢-flat" plan who paid 2¢/kWh at all hours, all of the PLAN dummy variables take zero values. Thus, the average consumption of those households on the 2¢-flat plan constitutes the mean reference load curve against which the effects of other plans are compared.[2] At the mean values of the weather, demographic, and appliance variables for the experimental households, the weekday reference load curve is

Period	i :	1	2	3	4	5
Share(%)	s_i :	10.7	11.5	15.3	19.7	42.3

The covariance analysis specification is effectively "model-free" in prices and allows each TOU rate plan to have an independent effect on the relative load in each of the five rate periods.[3] In Table 5 we summarize these effects in terms of the change in consumption relative to

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[1] We do not distinguish plans that apply peak prices five days per week from plans with the same peak rates that apply seven days per week. At the end of the section we present evidence supporting this grouping for weekday consumption.

[2] Two cents per kWh is merely a convenient reference value from which to measure load changes. The average price per kWh for experimental households on TOD rates was 3.47¢. During the experimental period the lowest price for Los Angeles households on standard rates rose from about 2.4¢/kWh to over 5¢/kWh.

[3] Subject, of course, to the constraint that the sum of the effects over all five periods is zero.

Table 5

TIME-OF-USE PRICE EFFECTS RELATIVE TO CONSUMPTION AT 2¢-FLAT PLAN

Plan No.	No. of House-holds	Peak Periods i	Peak Periods Hours	Prices per kWh Peak	Prices per kWh Off-Peak	Change in Peak Period Weekday Share	t-ratio	Change in Total Monthly Consumption kWh(%)	t-ratio
0A	56	--	00-24	2¢	2¢	--	--	--	--
0B	38	--	00-24	5¢	5¢	--	--	-3.7	(-.4)
Single Period Peak Plans									
1	71	1	09-12	5¢	2¢	-1.53	(-3.0)	-5.3	(-.8)
2	51	1	09-12	9¢	2¢	-2.40	(-4.3)	-0.0	(-.0)
3	18	1	09-12	13¢	2¢	-3.39	(-4.4)	-10.0	(-1.0)
4	34	2	12-15	9¢	2¢	-2.41	(-3.7)	-4.2	(-.5)
5	20	2	12-15	13¢	2¢	-1.07	(-1.4)	-7.1	(-.7)
6	18	3	15-18	5¢	2¢	-1.36	(-1.5)	.7	(.1)
7	69	3	15-18	9¢	2¢	-1.30	(-2.8)	-6.8	(-1.0)
8	68	3	15-18	13¢	2¢	-2.02	(-3.3)	-5.9	(-.8)
9	19	4	18-21	5¢	2¢	-.40	(-.4)	1.0	(.1)
10	53	4	18-21	9¢	2¢	-1.99	(-3.0)	-8.2	(-1.0)
11	51	4	18-21	13¢	2¢	-.86	(-1.3)	-6.3	(-.8)
12	143	5	21-09	5¢	2¢	-.85	(-.8)	-0.1	(-.0)

Multiple-Period Peak Plans

Plan No.	No. of House-holds	Peak Periods i	Peak Periods Hours	Prices per kWh Peak	Prices per kWh Off-Peak	Periods 1	Periods 2	Periods 3	Periods 4	Change in Total Monthly Consumption kWh(%)	t-ratio
13	31	3-4	15-21	7¢	2¢			-1.62	-2.53	-10.1	(-1.1)
14	105	2-4	12-21	5¢	1¢		-1.69	-1.19	-.87	1.3	(.2)
15	54	2-4	12-21	9¢	1¢		-1.30	-1.92	-1.63	-7.5	(-.9)
16	57	1-4	09-21	5¢	1¢	-1.55	-1.07	-.69	-.73	-5.1	(-.7)
17	69	1-4	09-21	9¢	1¢	-2.03	-2.18	-2.55	-.80	-15.6	(-2.0)

the 2¢ flat reference load, using estimated coefficients b_{im} in the peak periods.[1] The first two rows of the table are for the 2¢ and 5¢ flat-rate plans in which there is no incentive to shift loads. In subsequent rows the TOU plans are grouped by peak period, in ascending order of peak price within each group. The upper portion of Table 5 reports the 12 TOU plans with a single three-hour peak period. The reported values are the mean (percentage-point) changes in the peak period shares. For example, plans 1, 2, and 3 have peak prices of 5¢, 9¢, and 13¢ per kWh respectively at 9 a.m. to noon. These rates reduce the consumption share at this period by 1.5, 2.5, and 3.4 percentage points. The estimated pattern is highly consistent: relative to the reference load at a 2¢ flat rate, TOU rates reduce the share in every peak period, and in most cases higher TOU prices result in greater reductions. Most of the estimated effects differ significantly from the load at a 2¢ flat rate. Moreover, as shown in the lower part of the table, plans with 6-, 9-, and 12-hour peak periods (plans 13-17) cause reductions during every three-hour period that the peak rates are in effect.

At most of the peak price periods, there are two or three separate TOU plans with different price levels. The experimental design thus permits us to interpret the effects of each TOU rate plan in terms of the incremental change that successively higher peak prices have on relative peak loads. For example, in Table 5 TOU Plan 1 was estimated to reduce the 9 a.m. to 12 noon load 1.53 percentage points. Table 6 shows the plan-by-plan effects on the basis of incremental price effect.[2] Plan 1 has a 3¢ (5¢ - 2¢) differential between peak and off-peak prices so the estimated rate of change in the peak period weekday share per 1¢ increase in the peak period price is -.51. This value is shown as the first entry in Table 6. Plan 2 (9¢ peak, 2¢ off-peak) increases the price differential by an additional 4¢ = 9¢ - 5¢ and causes a further reduction in the 9 a.m. to 12 noon load share at the rate of -.22 per 1¢ difference in price.

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[1] The effect of plans on total consumption is discussed in the next subsection.

[2] These estimates are obtained by estimating Eq. (7) with the PLAN dummy variables redefined as price differences. Thus, PLAN_1 = 5¢-2¢, PLAN_2 = 9¢-5¢, PLAN_3 = 13¢-9¢,..., PLAN_{14} = 5¢-1¢, PLAN_{15} = 9¢-5¢,....

Table 6

RATE OF CHANGE IN PEAK PERIOD WEEKDAY SHARE PER 1¢ DIFFERENCE BETWEEN PEAK AND OFF-PEAK PRICE

Peak i	Period Hours	Single Peak Period Plans		Multiple Peak Period Plans 2 Period		3 Period		4-Period	
1	09-12	-.51*	(5/2) [a]					-.39*	(5/1)
		-.22	(9/2)					-.12	(9/1)
		-.25	(13/2)						
2	12-15	-.34*	(9/2)			-.42*	(5/1)	-.27*	(5/1)
		.33	(13/2)			.10	(9/1)	-.28*	(9/1)
3	15-18	-.45*	(5/2)	-.33*	(7/2)	-.30*	(5/1)	-.17	(5/1)
		-.09	(9/2)			-.18	(9/1)	-.46*	(9/1)
		-.08	(13/2)						
4	18-21	-.13	(5/2)	-.51*	(7/2)	-.22	(5/1)	-.18	(5/1)
		-.40*	(9/2)			-.19	(9/1)	-.02	(9/1)
		.28	(13/2)						
5	21-09	-.28	(5/2)						

* = significant at 95% confidence level, one-tailed test.

[a] Peak/off-peak prices in ¢ per kWh are shown in parentheses.

Plan 3 causes a similar -.25 incremental rate of load reduction. Thus, at the 9 a.m. to 12 noon peak period the estimated effects are consistent with a negatively sloped demand curve that becomes steeper at higher prices. In only a few cases is an incremental effect of a higher peak period price statistically different from zero. Thus, the overall pattern of estimated effects in most rate periods appears to be one in which the maximum rate of response results from the initial price difference, with notably smaller incremental effects occurring at higher price differentials.

TOU Price Effects on Total Consumption

The preceding results establish that TOU rates systematically alter the time of day distribution of the daily load. To determine whether TOU rates also affect total consumption, we first calculate monthly consumption at mean weather conditions for a month with the average 21.5 weekdays and 8.6 weekend days:

$$\bar{X}_j = 21.5 \sum_{i=1}^{5} \alpha_{ij} + 8.6 \sum_{i=6}^{10} \alpha_{ij} \qquad (8)$$

We then estimate an equation for total monthly consumption that is similar in form to the share equations:

$$\bar{X}_j = f(\mathrm{PLAN}_j, \mathrm{APPL}_j, \mathrm{DEMO}_j) + e_j \qquad (9)$$

$$= a + \sum_m b_m \, \mathrm{PLAN}_{mj} + \sum_k f_k \, \mathrm{APPL}_{kj} + \sum_k g_k \, \mathrm{PLAN}_{kj} + e_j .$$

Because total consumption varies across households from one hundred to several thousand kWh per month, we use an extensive set of appliance and demographic variables to capture systematic differences across households. Overall, the equation explains 72 percent of the variance in monthly weather-adjusted consumption between households.

The estimated effects of each TOU plan on total monthly consumption relative to consumption under a 2¢ flat rate are shown in the last two columns of Table 5. The coefficients are negative in all but three cases (although none of the three is statistically different from zero) and indicate that higher average rates per kWh do reduce overall electricity use, although only one coefficient is significantly different from zero.

Compared with a 2¢ flat rate, the 5¢ flat rate reduces total consumption 3.7 percent. Within groups of plans that have the same peak period there is some evidence that higher priced plans resulted in larger reductions in total consumption.

Summary of Analysis of Covariance

The covariance analysis of TOU price effects provides strong evidence that TOU rates alter the time-of-day distributions of residential loads and, less clearly, suggests that the rates also affect total consumption.

In an actual application of TOU rates, households will generally move from a declining-block or flat rate to a TOU rate that, on average, raises the same total revenue (apart from changes in level of use). Thus, it is not clear, a priori, whether total consumption can be expected to increase, fall, or remain constant--only a complete demand system analysis can address that question. But the expected effect of decreased peak and increased off-peak use is clear, and the covariance analysis of the experimental data is broadly consistent with the anticipated effects. Considering the relatively small number of households per experimental plan, the pattern of mean responses across rate plans is highly consistent with predicted economic behavior.

DEMAND SYSTEM ANALYSIS

To more fully exploit the rich experimental design of the Los Angeles experiment, we now specify the price effects in terms of a two-level system of demand equations. Congruence of the rate periods over all 17 TOU plans allows all households to be pooled into a single sample. The demand equation for each rate period includes major appliance and demographics variables that standardize the relative load curve across households with varying characteristics. The parameter estimates that we obtain enable us to reliably estimate the magnitude of the effects of each rate period's price on both total consumption and its distribution over the day.

In principle, one can postulate a utility function and derive a demand curve for each rate period. Each consumer would have a utility function containing the services of electricity consumed in each period and a composite commodity representing all non-electricity consumption. When maximized subject to a budget constraint, the utility function would imply restrictions on the specification and coefficients of the individual demand equations. This approach has been applied to several sets of data from TOU rate demonstration projects.[1] However, formally derived consumer demand systems are not easily adapted to the demand for intermediate goods and services. In practice such models have required either very strong assumptions on the structure of the underlying utility function or arbitrarily introducing other parameters--such as appliance stocks--into the utility function.

Our approach in this report is less formal. We model TOU effects at two levels--the effect on total consumption and on consumption by time of day relative to the reference load curve of a household at a 2¢ flat rate. By this artifice we usefully decompose a single reality--the change in kWh consumption at each rate period. We measure total consumption in kilowatt-hours. This aggregate, rather than the total expenditure on electricity that is used in neoclassical demand systems, allows straightforward comparison of results with previous estimates of electricity demand.

Introduction of a TOU rate will generally affect consumption in every rate period. First, a TOU rate will change the average price of electricity and thereby total monthly electricity consumption. Based on the household's consumption shares in each rate period at a 2¢ flat, the household's price index $\bar{p}$ for total kilowatt-hours will change from $\bar{p} = 2.0$ to some new $\bar{p} = f(p_1, \ldots, p_{10})$. Along with this overall reduction in total consumption is a shift in the relative load curve--the kWh shares at each period. For example, if the TOU rate has its peak price $p_1 = 5¢$ in period 1 and off-peak prices $p_2 = \ldots = p_{10} = 2¢$ in other periods, the expected effect is a reduction in both total use and the percentage of total consumption that occurs in period 1. The reduced share in period 1 will necessarily increase the percentage share in one or more other periods.

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[1] See, for example, the studies surveyed by Aigner and Poirier (1980) and Hendricks and Koenker (1980).

Relative Demand Estimates

In the complete demand system the kWh share equations are similar to equation (7) estimated in the covariance analysis, except that the dummy variable treatment of plan effects is replaced by a set of price terms, $b_{ik}p^*_k$, so that the kWh share equations become

$$s_{ij} = a_i + \sum_k b_{ik}p^*_k + \sum_k f_{ik}\ APPL_{kj} + \sum_k g_{ik}\ DEMO_{kj} + e_{ij}. \qquad (10)$$

The TOU prices are entered in relative form as

$$p^*_k = \log\ (p_i/p_5),\ k = 1,\ldots,4 \text{ weekdays}, \qquad (11)$$

$$p^*_k = \log\ (p_i/p_{10}),\ k = 6,\ldots,9 \text{ weekends}.$$

The implicit assumption is that consumers adjust consumption shares on the basis of the ratio of prices in different periods. The logarithmic transformation of this price ratio reflects the pattern observed in the covariance analysis--a diminishing proportional load-shifting effect as the absolute differences between peak and off-peak prices increase.

The five weekday and five weekend share equations were first estimated as specified in (10) by OLS with price variables p^*_k and the same demographic and appliance variables used in the analysis of covariance. The estimated own-price share coefficients were all negative and highly significant on a one-tailed (P = .05) t-test; most of the cross-price effects were positive, but only 6 of 15 were statistically significant by a two-tailed test.

Next, we tested to see whether households with particular appliances are sensitive to TOU rates. We augmented specification (10) to include additional sets of coefficients for the TOU prices interacted with major appliance variables. Statistically significant effects were found for both swimming pools and air conditioners; with this specification the estimated share equations are

$$s_{ij} = a_i + \sum_k (b_{ik} + c_{ik}POOL_j + d_{ik}AC_j)p_k^* \qquad (12)$$
$$+ \sum_k f_{ik}\ APPL_k + \sum_k g_{ik}\ DEMO_{kj} + e_{ij}.$$

The estimates of these coefficients appear in Table 7. TOU rates have quite modest effects on the relative loads of households having neither a pool nor an air-conditioner: only two of the estimated own-price share coefficients differ significantly from zero. In contrast, nearly all of the coefficients for households with a pool are significant, indicating that such customers do respond to TOU rates in both the peak and off-peak hours. Air-conditioned households are also significantly responsive but at somewhat smaller magnitudes. Rather than analyze these estimates in detail here, we will assess the TOU price effects in terms of full price elasticities after establishing the effect of TOU rates on total consumption.

Total Consumption Estimates

The Los Angeles experimental design was not limited to "revenue-neutral" TOU rates, and the final rates included considerable variation in the average price per kWh (cf. Table 1). This key feature enables us to obtain estimates of the effect of TOU rates on total consumption as well as its relative distribution by period.

Specification of the total consumption equation in the demand system is also similar to that used in the analysis of covariance (Eq. (7)) except that the set of dummy variables for TOU plans is replaced by a single price index $\bar{p}$ of total kilowatt-hours of electricity:

$$(13) \qquad \bar{X}_j = a + b\bar{p}_j + \sum_k f_k\ APPL_{kj} + \sum_k g_k\ DEMO_{kj} + e_j.$$

In these total consumption equations, price is in natural units; for example, for households on 2¢ and 5¢ flat rates, the index is $\bar{p}$ = 2¢ or $\bar{p}$ = 5¢. For household j on a TOU plan, facing TOU prices $p_{1j},\ldots,p_{10j}$, the price index is constructed to measure the ex ante costliness of

Table 7

WEEKDAY DEMAND SYSTEM PRICE COEFFICIENTS

Rate i	Period Hour		Coefficient of $\ell n(p_k/p_5)$				Coefficient of $\ell n(p_k/p_5)\cdot$POOL				Coefficient of $\ell n(p_k/p_5)\cdot$AC				
		k	1	2	3	4	1	2	3	4	1	2	3	4	R^2
1	09-12	s_1	-.36 (-2.22)	-.00 (-.02)	-.00 (-.01)	0.12 (0.61)	-3.01 (-8.48)	-.89 (-1.76)	1.43 (3.64)	0.42 (0.98)	-.72 (-1.86)	-.17 (-.30)	0.40 (0.94)	0.24 (0.53)	0.40
2	12-15	s_2	0.00 (0.00)	-.22 (-.93)	0.10 (0.53)	0.06 (0.30)	0.34 (0.89)	-2.33 (-4.35)	-.28 (-.67)	0.47 (1.02)	0.87 (2.13)	-.88 (-1.51)	0.28 (0.63)	-.37 (-.78)	0.35
3	15-18	s_3	-.12 (-.64)	-.14 (-.54)	-.19 (-.90)	0.07 (0.30)	1.73 (4.09)	-.60 (-1.34)	-1.52 (-3.27)	-.04 (-.08)	0.77 (1.66)	0.99 (1.52)	-1.14 (-2.27)	-.60 (-1.12)	0.24
4	18-21	s_4	0.09 (0.49)	-.24 (-.91)	0.17 (0.79)	-.44 (-1.89)	1.48 (3.42)	0.13 (0.21)	-.77 (-1.62)	-.85 (-1.62)	-.01 (-.01)	0.96 (1.44)	-.17 (-.32)	-.50 (-.91)	0.27
5	21-09	s_5	0.38 (1.01)	0.61 (1.16)	-.08 (-.19)	0.19 (0.42)	-.53 (-.63)	3.90 (3.25)	1.15 (1.24)	-.00 (-.00)	-.91 (-1.00)	-.90 (-.70)	0.63 (0.63)	1.24 (1.16)	0.26

Note: t-ratio in parentheses

electricity under its TOU rate plan. The household's reference load curve at the 2¢ flat rate, given its demographic and appliance characteristics, has the estimated shares s^*_{ij} from Eq. (12). The price index

$$\overline{p}_j = \sum_i s^*_{ij} \, p_{ij} \tag{14}$$

gives household j's average cost per kWh under the TOU rates prior to load shifts induced by the rates.[1] The estimated price index coefficient is -21.2 (t=3.4), implying a price elasticity of total consumption of -.13 at mean levels of consumption and prices. The air conditioner and pool variables interacted with the price index do not result in significant coefficients, indicating that changes in total consumption are similar for all households at the same price index value.

The experimental results thus establish that TOU rates do change total consumption in the direction predicted by consumer demand theory. Because the overall elasticity of -.13 is estimated by controlling for an extensive list of major appliances and demographic factors, it approaches a "pure utilization" measure of price response. It compares, for example, with price elasticity estimates of -.06 to -.08 in Lillard and Acton's (1980) analysis of the seasonal component of the Los Angeles experiment and -.35 to -.50 in Acton, Mitchell, and Sohlberg's (1980) analysis of non-experimental data in Los Angeles county. The much larger elasticity estimates reported by other researchers using non-experimental data, such as those summarized in Taylor's (1975) survey, were obtained in more aggregative studies that contain only limited adjustment for variation in appliance stocks.

Appliance and Demographic Effects

Because the total monthly consumption equation (9) is specified in linear form the estimated coefficients provide direct estimates of the mean consumption rates of each type of appliance. These values, reported

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[1] This definition of $\overline{p}$ avoids the simultaneity bias that would be introduced by using ex post share weights s_{ij}.

in Table 8, are reliably estimated for most of the major appliances and are consistent with the results obtained from small-sample studies of individual household appliances in nearly all cases.[1] For example, an electric water heater is estimated to consume 140 kWh/month (exclusive of its use with a clothes washer or dishwasher) and a color television set 46 kWh/month. The coefficients for air conditioners (163 kWh/mo) and space heaters (111 kWh/mo) are the estimated average monthly (year-round) consumption for a household with these appliances facing average Los Angeles temperatures.

The results for the demographic variables in Table 8 confirm the importance of housing characteristics and family size, as well as income, in explaining household-specific variation in electricity use. Because the services of electricity are not consumed directly, these variables are proxies for unmeasured appliances, rates of utilization, and tastes that affect overall consumption. The implied income elasticity, .11 at the sample mean, is perhaps best interpreted as the combined effect of greater utilization of a given stock of major appliances plus ownership of minor, unmeasured appliances. The principal effect of income is probably reflected through the long-run decisions to purchase appliances and determine housing characteristics.

Major appliances and demographic characteristics also affect the timing, as well as the level, of a household's electricity consumption. The estimated coefficients of these variables for the five weekday share equations are shown in Table 9. They indicate, for example, that relative to the reference load curve, a flat-rate household with a swimming pool consumes some 4 percentage points more of its electricity (which is greater in aggregate) during the morning and early afternoon (periods 1 and 2), about 1 percentage point more in the late afternoons, and a lesser share in periods 4 and 5. Similarly, households with electric dryers and washing machines have higher relative loads in the early part of the day and lower loads in the evening and overnight periods. The relative load curve is also shifted in the expected way by the weather-sensitive appliances.

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[1] See, for example, Parti and Parti (1980).

Table 8

EFFECTS OF APPLIANCES AND DEMOGRAPHIC VARIABLES ON TOTAL MONTHLY CONSUMPTION

Item	Monthly Consumption (kWh)	t-Ratio
Appliance Variables		
Swimming pool (at mean area of 120 sq. ft.)	368	13.8
Water heater	140	2.7
Clothes washer (with electric water heater)	73	1.2
Dishwasher (with electric water heater)	50	0.8
Clothes dryer	65	3.4
Stove		
All electric	71	4.2
Combination	58	1.6
Microwave oven	51	2.4
Refrigerator	64	1.8
Frost-free refrigerator	149	3.3
Freezer	104	6.1
Black and white television	18	1.9
Color television	46	4.0
Air conditioner	163	6.7
Electric space heater	111	3.4

Demographic Variables

Item	Coefficient	t-Ratio
Family income (log)	60	4.7
Family size (log)	174	7.6
Number of rooms (log)	99	2.6
Housing rental value (log)	108	5.1

Table 9

COEFFICIENTS OF WEEKDAY SHARE EQUATIONS
(at 2¢ flat rate)

Item	Coefficients in Period[a]				
	1	2	3	4	5
Appliance Variables					
Pool	*4.06*	*4.11*	*1.05*	*-2.94*	*-6.28*
Electric water heater	*1.35*	0.55	-.43	*-1.57*	*0.10*
Clothes dryer	*1.24*	0.52	0.25	*-.54*	*-1.47*
Clothes washer (with water heater)	0.62	1.01	0.28	-.75	-1.16
Stove (all electric or combination	0.22	-.04	*1.24*	-.29	-1.12
Microwave oven	0.08	0.05	*-.61*	-.33	0.81
Frost-free refrigerator (increment over refrig.)	*0.83*	*0.69*	-.19	*-1.57*	*0.23*
Freezer	*0.36*	0.03	-.15	*-.99*	*0.76*
Color television	0.07	0.09	0.04	0.03	-.22
Air conditioner	-0.28	*0.95*	*1.74*	0.25	-2.72
Heater	0.54	-.11	-.50	-.06	0.13
Demographic Variables					
Income (log)	-.15	*-.44*	*-.63*	0.15	1.07
Family size (log)	-.11	*0.72*	*1.11*	0.10	-1.82
Rooms (log)	-.43	-.56	*-1.13*	-.39	2.50
Monthly or housing value (log)	.05	-.23	-.15	*0.55*	*-.22*

[a] Italicized coefficients are significant at the .05 level.

At mean temperatures the presence of an air conditioner increases the relative load from noon to 9 p.m., with the greatest effect occurring in mid-afternoon. Electric space heating causes relative loads to be higher in the morning and overnight. Multi-person households have higher afternoon loads when children are likely to be at home.

MISCELLANEOUS RESULTS

The richness of the Los Angeles experimental data base invites numerous tests of special hypotheses. We report very briefly a few that have been conducted to date.

Testing for Weekday to Weekend Load Shifts

For one-half of the TOU households the price during all weekend hours was the off-peak price. For the other households the peak hours and prices applied 7 days a week. The first group ("five-day" households) therefore had some incentive to shift weekday electricity consumption into weekend hours. If such shifting occurs, it will reduce the total consumption on weekdays by five-day households relative to seven-day households. It could also alter the distribution of weekday shares.

We tested for such effects in the demand system by separately estimating total weekday and total weekend consumption equations, distinguishing the five-day households by a dummy variable. Both the weekday and weekend dummy-variable coefficients were positive and insignificant. When the five-day dummy variable is included in the kWh share equations it is also insignificant. There is therefore no evidence that off-peak weekend rates shift load out of weekday periods.

Effect of Lump-Sum Compensation Payments

Some households, at their rates of consumption for one year prior to the beginning of the experiment, would have incurred a higher annual electricity bill under their experimental rate plan. These households received quarterly lump-sum checks for this difference throughout the experiment, regardless of their level or pattern of electricity use during the experiment. If households "earmarked" their compensation payment for the higher bill they would otherwise pay on TOU rates, they might display no response to the TOU rate. To test this hypothesis, households receiving compensation were randomly split into two groups, with 178 receiving full quarterly payments. The second group of 75 households received one-half of their compensation payments quarterly and the balance in a lump sum at the termination of the experiment--30 months later.[1] If earmarking were taking place, households receiving half-payments quarterly should have responded differently to TOU rates than those receiving full payments after accounting for all other factors.

Dummy variables indicating those households that received full payment and those receiving half-payment are significantly positive in the total consumption equation. Although this might suggest that households receiving payments were less responsive to the marginal prices of electricity, the positive coefficients may simply reflect the positive correlation across the sample between consumption and the occurrence of a compensation payment: because of the declining-block rate in effect prior to the experiment, households receiving compensation payments were predominantly large consumers of electricity who previously had the lowest average price per kWh. The coefficients of the full and half-payments variables are statistically indistinguishable. This result refutes the earmarking hypothesis and allows us to assume that households receiving compensation payments do not differ from other experimental households in their responses to TOU rates.

Relative Price Specification

In Eq. (12) we assume that the quantity shares in each rate period are functions of TOU prices in relative terms (e.g., p_i/p_5). Thus, standardizing for household characteristics, the relative loads of households on 2¢ flat rates and on 5¢ flat rates should be the same. A test of this hypothesis is provided by including a dummy variable for 5¢ flat plans in Eq. (12). It was insignificant in each rate period.

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[1] Households receiving compensation payments were randomly allocated to the full or half-compensation themes with a 50:50 probability, subject to the restriction that no household would receive less than $1 quarterly if assigned to the half-compensation scheme.

V. TOU DEMAND ELASTICITIES

In this concluding section we report the matrix of full own- and cross-price elasticities of demand that are obtained from the hybrid model. We compare these estimates to own-price elasticities obtained in demand system studies of other TOU experiments. Finally, we illustrate the use of the hybrid model to predict the changes in load that would attend the introduction of a particular TOU rate plan not tested in the experiment itself.

PRICE ELASTICITIES OF DEMAND

After the effects of weather (and other time-dependent variables) have been netted out, electricity demand (x_i) in period i is a function of the vector of TOU prices (p) and a vector of household-specific characteristics (Z). The demand system takes the general form:

kWh share equations

$$s_i = \frac{x_i}{x} = s_i\left(\frac{p_1}{p_n}, \ldots, \frac{p_{n-1}}{p_n}; Z\right), \quad i = 1, \ldots, n \tag{15}$$

total consumption equation

$$x = x(\overline{p}; Z) \tag{16}$$

where $\overline{p} = \sum_k s_k^* p_k$, $s_k^* = s_k\left(\frac{p_1^0}{p_n^0}, \ldots, \frac{p_{n-1}^0}{p_n^0}; Z\right)$

is the price index of the vector of TOU rates p evaluated using the kWh shares at a reference price vector p^0 (e.g., 5¢ flat rate).

The price elasticity η_{ij} of consumption in rate period i with respect to a change in the price in period j can be represented in terms of the elasticities of the share equations

$$\varepsilon^{s_i}_{p_j} \equiv \frac{\partial s_i}{\partial p_j} \frac{p_j}{s_i} \tag{17}$$

and the elasticity of the total consumption equation

$$\varepsilon^{x}_{\bar{p}} \equiv \frac{\partial x}{\partial \bar{p}} \frac{\bar{p}}{x} \quad . \tag{18}$$

To see the relation between share elasticities and total elasticity of demand define

$$w_j = \frac{p_j x_j}{\bar{p} x} \tag{19}$$

the expenditure in period j relative to the cost of total consumption at the index price. Then the full elasticity can be written

$$\eta_{ij} = \varepsilon^{s_i}_{p_j} + \varepsilon^{x}_{\bar{p}} w_j \ .^{1} \tag{20}$$

The resulting elasticity η_{ij} is a "full, uncompensated" price elasticity that includes the changes in total expenditure on electricity and in real income that result from a change in the period j price.

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[1] Write $x_i = s_i x$. Then

$$\eta_{ij} = \frac{\partial x_i}{\partial p_j} \frac{p_j}{x_i} = \frac{\partial s_i}{\partial p_j} \frac{p_j}{x_i} x + s_i \frac{\partial x}{\partial p_j} \frac{p_j}{x_i}$$

$$= \frac{\partial s_i}{\partial p_j} \frac{p_j}{s_i} + \frac{x_i}{x} \frac{\partial x}{\partial \bar{p}} \frac{\partial \bar{p}}{\partial p_j} \frac{p_j}{x_i}$$

The matrix of full price elasticities for the weekday model are reported in Table 10. Because the price elasticity of total consumption is sensitive to the level of the price index, we evaluate the full price elasticities in terms of a reference price of 5¢. At this level the total consumption elasticity is -.19.[1] The parameters are first calculated at the mean consumption shares observed in the sample, assuming no swimming pool or air conditioner. These appliances are then introduced separately and together. The results show the sensitivity of TOU response to these appliances; when a household has either a pool or an air conditioner it has both a different initial relative load curve and a greater propensity to shift load.

For households with no pool or air conditioner the own-price elasticities are quite small, -.05 to -.13. The cross-price elasticities are smaller and negative. Such households tend to make small reductions in loads in all periods when any TOU price is increased.

Households with a pool, an air conditioner, or both are considerably more responsive. Own-price elasticities range up to -.13 to -.32 with greater values found in the morning and afternoon and lowest values in the period 6 p.m. - 9 p.m. Even at this early evening period, the own-price elasticity for households with both pool and air-conditioner is roughly double that for households lacking both pieces of equipment. Cross-price elasticities are also larger and of mixed signs. Households with these appliances increase net loads in some off-peak periods.

$$= \varepsilon^{s_i}_{p_j} + \frac{x_i}{x} \left(\frac{\partial x}{\partial \bar{p}} \; \frac{\bar{p}}{x} \right) \frac{x}{\bar{p}} \; \frac{\partial \bar{p}}{\partial p_j} \; \frac{p_j}{x_i}$$

$$= \varepsilon^{s_i}_{p_j} + \varepsilon^{x}_{\bar{p}} \; \frac{s_j p_j}{\bar{p}} = \varepsilon^{s_i}_{p_j} + \varepsilon^{x}_{\bar{p}} \; w_j$$

[1] This value of price elasticities for total consumption differs from the value reported above (-.13) because the former value corresponded to an average TOU price index value of 3.47¢/kWh.

Table 10

FULL PRICE ELASTICITIES OF DEMAND (at p_i = 5¢/kWh)

Households Without Pool or Air Conditioner

Weekday hour	kWh in Period i	Price in Period 1	2	3	4	5
09-12	1	-.06	-.02	-.04	-.03	-.08
12-15	2	-.02	-.05	-.03	-.03	-.08
15-18	3	-.03	-.04	-.05	-.07	-.07
18-21	4	-.02	-.04	-.02	-.07	-.08
21-09	5	-.01	-.01	-.03	-.04	-.13

Households with Pool and Without Air Conditioner

	1	2	3	4	5
1	-.27	-.07	.08	.03	.11
2	.01	-.17	-.07	.02	.09
3	.09	-.07	-.16	-.01	.03
4	.08	-.04	-.05	-.10	-.02
5	-.02	.09	.03	-.02	-.20

Households Without Pool and With Air Conditioner

	1	2	3	4	5
1	-.12	-.08	.04	-.03	.02
2	.06	-.21	.08	-.03	-.05
3	.03	.00	-.09	-.05	-.05
4	-.02	.04	-.03	-.08	-.07
5	-.03	.01	-.04	-.00	-.10

Households with Pool and Air Conditioner

Weekday hour	kWh in i	Price in Period 1	2	3	4	5
09-12	1	-.32	-.12	.13	.03	.17
12-15	2	.06	-.28	.01	.02	.09
15-18	3	.13	-.03	-.19	-.04	.02
18-21	4	.07	.05	-.07	-.13	-.03
21-09	5	-.04	.12	.02	.01	-.20

COMPARISON WITH OTHER TOU PRICE ELASTICITY ESTIMATES

Using data from the first 18 months of the Los Angeles experiment, Manning and Acton (1980) conducted exploratory data analysis using Box-Cox transformations and selected a log-linear specification for single equation estimation. Their demand equations make consumption in each weekday rate period a function of weather, appliance and demographic variables, and TOU prices alone and with appliance interactions. The own-price elasticities for households at the mean characteristics of the sample range from -.05 to -.10; cross-price elasticities are generally insignificant. When mean household characteristics are combined with a swimming pool, own-price elasticities lie between -.07 and -.46 during daytime hours. These values are in general agreement with the hybrid model estimates in Table 10.

Data from the Connecticut, Arizona, and Wisconsin TOU experiments have been analyzed in neoclassical demand system models by several research groups.[1] These models typically estimate "partial" elasticities that are conditional on a fixed amount of expenditure on electricity. As Hendricks and Koenker (1980) make clear, the value of the partial elasticity in a given rate period is a direct function of both the quantity share and the TOU price in that period. Consequently, partial elasticities cannot be compared across rate periods or across different experiments.

By accounting for the price elasticity of total consumption one can calculate full (unconditional) price elasticities from the estimated partial elasticities. However, in the case of these three experiments there was insufficient variation in the average price per kWh to obtain reliable estimates of the aggregate price elasticity. Nevertheless, Hendricks and Koenker assumed that the elasticity of total consumption is -.10 and computed full TOU price elasticities for the various demand system studies. With this assumption they find that the range of own-price full TOU elasticities is approximately -.1 to -.3.

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[1] See Aigner and Hausman (1980), Atkinson (1977, 1978), Caves and Christensen (1980), Lau and Lillard (1978), Lawrence and Braithwait (1977), and Miedema et al. (1978).

The estimate of the total consumption price elasticity in our hybrid model at a 5¢ flat rate is -.19, somewhat greater than that assumed by Hendricks and Koenker. The full own-price elasticities estimated here range from -.05 to -.13 for households with no pool or air conditioner, and from -.13 to -.32 for households with both (Table 10). Overall, the own-price elasticities from the various experiments appear to be in general agreement.

No full cross-price elasticities have been published for the demand system models of the other experiments. As a result, we have no direct basis for comparing our cross-elasticity estimates, which show that most of the load shifting induced by TOU rates is due to households with pools or air conditioners.

AN ILLUSTRATIVE TOU RATE

Suppose that initially a 5¢/kWh flat rate prevails. In the Los Angeles sample, households with the mean appliance and demographic variables, and both a pool and air conditioner, would use an average of 954 kWh per month at average weather conditions. The weekday distribution of this load is shown in Table 11.

Introduction of a 9¢/kWh rate from 09-18 daily and 3¢/kWh at other hours would establish peak prices during three rate periods. Although this particular tariff was not included as one of those tested experimentally, the hybrid model can readily be used to predict the household's new load curve. Based on the average household's load under the flat rate, the TOU rate would raise the average price per kWh from 5¢ to 5.94¢ and reduce total monthly consumption to 934 kWh. The effect on loads in each rate period are calculated from the respective share equations by inserting the 9¢ and 3¢ prices in the appropriate periods. As shown in the table the net effect would be to decrease loads in each of the three peak price periods and increase usage in the off-peak hours.

Table 11

WEEKDAY LOAD CHANGES OF AN ILLUSTRATIVE TOU RATE: AVERAGE HOUSEHOLD WITH POOL AND AIR CONDITIONER

Item	Period 1	Period 2	Period 3	Period 4	Period 5
Flat Rate					
Price per kWh	5¢	5¢	5¢	5¢	5¢
Share (%)	13.7	15.5	17.5	17.5	35.7
kWh/day	4.4	5.0	5.6	5.6	11.4
TOU Rate					
Price per kWh	3¢	9¢	9¢	9¢	3¢
Share (%)	15.4	21.1	13.7	15.7	43.1
kWh/day	4.8	3.8	4.3	4.9	13.5

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