EVALUATING TIME-OF-DAY ELECTRICITY RATES FOR RESIDENTIAL CUSTOMERS

PREPARED FOR THE LOS ANGELES DEPARTMENT OF WATER AND POWER

JAN PAUL ACTON, BRIDGER M. MITCHELL

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PREFACE

The Los Angeles Electricity Rate Study—a five year project begun in 1975—is designed to yield information about the effects of alternative pricing structures for residential consumers. The experimental plans include time-of-day, seasonal, and time-invariant rates for approximately 1800 households over a 30 month period. The study is being conducted jointly by the Los Angeles Department of Water and Power and The Rand Corporation, with partial funding from the Department of Energy.

This report\(^1\) presents the basic framework for analyzing the changes in economic well-being from introducing time-of-day rates. Although consumer attitudes and administrative feasibility are also important to an overall assessment of such rates, the report concentrates on the more quantitative measures of changes in consumers' and producers' welfare.

The report should be of interest to electric utilities and regulatory bodies investigating consumer responses to new rates. It should also be of more general interest to economists and policy analysts for the analytic framework it provides for evaluating welfare gains from the introduction of more complicated pricing policies in a regulated industry.

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

\(^{1}\)This report is also scheduled for inclusion in Regulated Industries and Public Enterprise: European and United States Perspectives, edited by Bridger M. Mitchell and Paul R. K. Kleindorfer, to be published by Lexington Books.
-iv-

SUMMARY

Although practiced for several decades in some European utilities, peak-load pricing of electricity has only recently received serious attention from the U.S. electricity industry. Because the costs of electricity supply vary with the system load—usually on a fairly regular daily cycle—peak load pricing more accurately represents the cost of electricity. If it cost nothing to meter and bill each customer for his use during peak and off-peak hours, peak-load pricing would undeniably improve the efficient use of resources and would result in more equitable billing.

But because time-of-day pricing generally requires major investments for new meters, the introduction of peak-load rates raises a fundamental benefit-cost question: Do the social benefits of pricing electricity more in accord with its cost exceed the metering investment that would be required?

For large industrial and commercial customers, only modest percentage changes in electricity use will lead to benefits in excess of metering costs, so new rate structures are clearly desirable for them. In contrast, it may not be worthwhile for residential customers to shift to time-of-day rates at the present costs of metering. Instead, a selective approach may be called for that either gives households the choice between a standard rate or a time-of-day rate, or that requires time-of-day rates for only a fraction of the residential customers. The particular subclass of customers for whom the expected benefits would exceed the metering costs must be identified by the utility using indicators that are readily available.

Welfare economics provides the basic framework for judging whether the benefits of time-of-day pricing exceed its metering costs. Changes in consumers' and producer's surplus measure the increased economic efficiency with which electricity is used. These gains must be compared with the added costs of installing and operating the new pricing structure. If the specific social objective is to promote greater equity in electricity bills—in the sense that prices will more
accurately reflect a variation in costs of supply to each group of customers—then a value can be assigned to this equity objective. Improved billing equity can be added to measures of improved efficiency when comparing gains with added costs.

For the present analysis, however, we consider only the gains in efficiency for the benefit-cost comparison. We assume that apart from the metering expense, the new rates do not change the utility’s profits. For the representative customer (whose electricity consumption during the peak period is proportional to the residential average), peak-load rates represent an unambiguous gain; he can change the amount and timing of his electricity use either to reduce his bill or to increase his consumption in off-peak hours. If these gains in consumer surplus are sufficiently large, the consumer can afford to pay the rental price of a new meter and still realize a net benefit.

Empirical results for this study are based on data from the Los Angeles Electricity Rate Study, a 30-month experiment with 1800 households using either time-of-day, seasonal, or time-invariant electricity rates. The study found that the price elasticity of demand increased steadily with the total monthly use of electricity and that price responsiveness was markedly greater in households having certain types of appliances. (For example, households with swimming pools displayed own-price elasticities approximately five times as great as households without pools.)

Time-of-day pricing could not be justified for the entire residential class. Instead, only a subset of customers displayed a sufficient degree of price responsiveness to offset the added metering costs. For illustration the study assumed that meters cost $150 installed and were amortized over 15 years. For all households, the average gain in welfare exceeded the metering costs only when consumption was above 1100 kwh/month. Although only 4 percent of the residential users in Los Angeles go above that level, they nevertheless account for over 17 percent of residential use. However, for households with swimming pools, the average welfare gain exceeded assumed metering costs when consumption was above 800 kwh/month. These
particular values depend on the assumed costs of meters, the level and timing of peak charges, and the characteristics of the residential population. Consequently, some consumers who are more responsive than the average would benefit from time-of-day rates at lower usage levels. Of course, the size and characteristics of the subclass in other utility systems will generally be different and the break-even point will also be different.

In many cases, the change in an individual customer's bill does not exactly parallel the change in social welfare. These cases complicate the introduction of time-of-day rates on an optional basis. In some situations, the customers' bills would fall under the new rate, but welfare would not increase sufficiently to cover the metering cost. For example, in Los Angeles customers with electric space heating consume a disproportionate amount of their electricity in off-peak periods and could reduce their bills simply by switching to a time-of-day rate without having to make any adjustment in their patterns of use. In that case, time-of-day rates might increase economic equity by more closely aligning the customers' bills with their actual costs of service. However, without changes in customer use, the rates would provide no efficiency gain to the electric utility and yet still expend resources on new meters.

Conversely, there are other customers whose bills increase even when the welfare gains exceed the metering cost, which makes it unlikely that a voluntary program would be successful. For example, Los Angeles customers with air conditioning typically consume an increasing proportion of their electricity during peak periods as their total monthly use rises. Although their usage adjustments to time-of-day rates might offset the metering costs, such customers will not voluntarily choose a time-of-day rate that would increase their monthly bills. Even if consumers' bills would be lower after these adjustments, they are unlikely to switch to an optional rate, which at their former use pattern would cost more.

The difficulties of using a voluntary plan to introduce time-of-day rates leave the policymaker with two options: (1) make time-of-day rates mandatory for the appropriate residential subclass or (2) convert
the present standard rates to redesigned rate structures that reflect the average cost of that subclass more accurately, thus making optional time-of-day rates attractive for only those customers who realize net welfare gains.

In the latter case the standard rates for the subgroup of customers with higher-than-average peak period consumption must be increased, either uniformly or possibly in the form of an increasing block rate structure. At the same time, if another group of consumers has lower-than-average peak period consumption, their standard rate should be reduced so that they won't choose to switch to the time-of-day rate merely to lower their bills.

At the foreseeable costs of new meters, time-of-day rates will benefit only a fraction of the residential class. The level of monthly electricity consumption provides a useful guide to selecting the appropriate subclass. If the new rate is optional, it will be necessary to adjust the standard rate, and perhaps to replace it by one or more block rate structures that closely reflect differences in peak period consumption and the use of selected major appliances.
ACKNOWLEDGMENTS

This report benefited from the advice, support, and critical comments of many people. Harrison Call, Jr., Michael T. Moore, and Dennis Whitney of the Los Angeles Department of Water and Power were active in the evaluation and guidance of this study from the outset. Willard Manning and James Smith of The Rand Corporation, Olivier Koenig of Electricité de France, Paul Kleindorfer of the University of Pennsylvania, and Hethie Parmesano of the Los Angeles Department of Water and Power provided extremely useful comments on an earlier draft. Becky Goodman, Mollye Merideth, Don Negri, Frayda Seigal, Sandee Sims, and Helen Turin of Rand worked on editing and producing the final report.
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I. INTRODUCTION

Peak-load pricing—an established feature of ratemaking in many European electricity utilities—was a concept foreign to the practice of virtually all electricity utilities in the United States until the mid-1970s. A growing public concern over environmental issues and disruptions of energy supplies caused a few state regulatory commissions to institute broad-ranging hearings into electricity rate structures in the early 1970s. These proceedings led to the first commission order to establish seasonal and time-of-day rates for very large electricity consumers—primarily large industrial firms and major office buildings. With the passage of the 1978 National Energy Act, all state commissions and larger publicly owned utilities are required to consider the suitability of a variety of unconventional rate structures, including forms of seasonal and time-of-day rates.

A recent study established that peak-load pricing practices in European utilities have indeed led to significant gains in economic efficiency. That experience, projected to U.S. conditions, suggests annual efficiency gains of several billion dollars in the industrial sector alone.1 With the shift in regulatory policy and the accumulating evidence showing the economic benefits of industrial peak-load rates, time-of-day rates for customers supplied at high voltage should become the norm in U.S. utilities during the next few years.

The desirability of peak-load rates for residential customers in the United States is far less clear. A major urban area contains hundreds of thousands of residences. Most of these customers use considerably less than 1000 kilowatt-hours of electricity per month and have limited possibilities for reducing or shifting peak-hour use. With present technology, the added cost of installing time-of-day meters may be high enough to outweigh the benefits of more efficient consumption patterns for many consumers.

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1See Mitchell, Manning, and Acton (1978, Ch. 8).
Residential time-of-day rates may need to be targeted to a particular subclass of consumers for whom the benefits will exceed the metering costs. In this report we consider the design of a time-of-day rate structure for residential consumers in terms of this targeting requirement. In Section II we analyze the welfare economics of shifting from uniform to peak-load rates. This analysis measures the gains to producers and consumers that are achievable at the cost of new meters. It also highlights the redistributive effects such rates can have. In Section III we use preliminary data from an extensive 30-month test of residential peak-load rates to quantify patterns of welfare changes and cost redistributions that would accompany time-of-day rates. We find that if time-of-day rates were applied to all residential customers, the additional costs of metering would greatly exceed the benefits of more efficient energy use. However, if new rates are offered to subclasses of residential users with large consumption levels or high price elasticities, considerable net improvements in welfare can be achieved.
II. BASIC WELFARE ANALYSIS OF PEAK-LOAD PRICING

To analyze the welfare implications of introducing time-of-day (TOD) rates in theoretical terms we will consider changes in aggregate welfare—measured by the sum of consumers' and producer's surplus—and redistribution of costs among consumers. This measure gives equal weight to changes in each individual's well-being and emphasizes the allocative function of prices. With such a welfare measure, increasingly complex rates are desirable only up to the point that the gains in producer and consumer well-being are not offset by added metering costs.

Some rate-setting bodies may also aim to use a more complex pricing structure to better reflect the costs of serving individual customers. Such equity objectives could justify a new rate structure even when the incremental costs of change exceed the efficiency gains. 2

For this analysis we adopt the assumptions of the classical Boiteux-Steiner peak-load pricing model. Although our specific illustration is made in electricity, the basic methodology is general to a class of regulated industries. There are two tariff periods, peak and off-peak. In each period, electricity can be supplied at constant marginal costs $mc_1$ or $mc_2$. Any fixed costs are recovered by a uniform entry fee (the customer charge). Demand is at a uniform level, $x_1$ and $x_2$, in each period; total consumption is given by $x = x_1 + x_2$. We assume that no consumer is excluded from the market by the tariff.

TIME-IN Variant AND TOD RATES

Under these conditions the optimal two-part tariff $(E, \hat{p})$ has an entry fee $E$ and a uniform price $\hat{p}$ that applies to consumption in both peak and off-peak periods. The optimal $\hat{p}$ is a weighted average

---

2 The analysis presented here can be modified to give differential weight to certain individuals and to incorporate other distributive objectives.
of $mc_1$ and $mc_2$, where the weights are the slopes of the peak and off-peak compensated demand curves in the peak and off-peak periods:

$$\tilde{p} = \frac{a}{a + b} mc_1 + \frac{b}{a + b} mc_2,$$  \hspace{1cm} (1)

where $a = \beta x_1 \beta p_1 + \beta x_2 \beta p_2$, $b = \beta x_2 \beta p_1 + \beta x_2 \beta p_2$. These weights balance the distortions between the common $\tilde{p}$ and the different values of marginal costs in each period. Because marginal costs are weighted by demand slopes, rather than demand levels, the revenues from per-unit charges, $\tilde{p}_x$, will not necessarily collect all of the variable costs. The per-customer entry fee $E$ is chosen to recover any difference plus all fixed costs.

If the utility is not already engaged in peak-load pricing it will not readily be able to assess these demand slopes. Instead of taking $\tilde{p}$ as given by Eq. (1), we will assume that the uniform price, $\bar{p}$, is set equal to the quantity-weighted average of the marginal costs

$$\bar{p} = \frac{x_1}{x} mc_1 + \frac{x_2}{x} mc_2$$  \hspace{1cm} (2)

and that before introducing PLP, the entry fee exactly recovers the fixed costs. 4

Before proceeding, we may contrast the problem considered here with that addressed in the nonlinear pricing literature for a homogeneous good. 5 When a high uniform price would exclude some consumers from the market, a nonlinear price structure, $R(x)$, specifying the consumer's expenditure as a function of consumption $x$, can increase welfare. The public utility can practice price discrimination by choosing the $R(x)$ function so that marginal prices $p(x) = dR(x)/dx$ vary with $x$ yet still exceed marginal cost. This pricing policy

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3 See Roberts (1979); Rees (1976).
4 Existing uniform price tariffs in some utility systems, including Los Angeles, approximate this formulation.
5 See, for example, Willig (1979b).
generates larger total contributions than a uniform price and allows entry prices for small consumers to be reduced.

For some distributions of consumer demand the optimal nonlinear expenditure function can be approximated by a declining-block tariff or by a series of optional two-part rates. Both types of rate structures have been used in the electricity supply industry. At the rates prevailing in industrial countries, however, practically no consumer is excluded from purchasing electricity, so that the entry fee can be set to recover all fixed costs and a uniform $p$ can be charged for customers of all sizes. Thus, nonlinear pricing produces no welfare gains when electricity is regarded as a homogeneous good, the prevalence of declining-block rates notwithstanding.

Shifting to peak-load pricing eliminates the distortions that result from the divergence of the average price from the marginal cost in each period. But unlike the introduction of nonlinear pricing, which can be accomplished merely by changing the computer billing algorithms, peak-load TOD rates require incremental investments in meters for each customer.\(^6\) This added fixed cost may more than offset the efficiency gains for most residential customers.

---

Change in Welfare

Leaving the entry fee $E$ fixed, we can evaluate the welfare gain in moving from an average price $\bar{p}$ to peak and off-peak rates $p_1 = mc_1$ and $p_2 = mc_2$ as follows: Figure 1 shows the peak period consumption $\bar{x}_1$ and off-peak period consumption $\bar{x}_2$ under a uniform price $\bar{p}$. A shift to rates $p_1$, $p_2$ will induce new consumption levels $x_1$, $x_2$ as a result of the own-price elasticities in each period as well as the cross-price elasticities between periods that reflect the substitution or complementarity of peak and off-peak electricity.

The resulting change in welfare ($\Delta W$) is given by the sum of the changes in consumers' surplus ($\Delta CS$) and producer's surplus ($\Delta PS$). In

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\(^6\) Seasonally varying rates can be implemented with existing kilowatt-hour meters. Because the additional billing and meter reading costs are small, seasonal rates will result in welfare gains whenever there are systematic seasonal variations in marginal costs.
Figure 1, consumers' surplus is reduced by approximately the trapezoidal area \( \bar{p}p_1\bar{e}c \) in the peak period and increased by the area \( p_2\bar{f}g \) in the off-peak period. At the initial consumption quantities, the change in producer's surplus is the difference between the increased revenue \( \bar{p}p_1dc \) in the peak period and the decline \( p_2\bar{f}gh \) in the off-peak period. Because the new prices are equal to marginal costs, the changes in consumption do not result in any additional change in producer's surplus. The welfare change is the algebraic sum of these areas, the triangles \( T \) plus \( U \).

This measure of the change in welfare is based on two assumptions: linear demand curves and insensitivity of consumers' surplus to the order in which peak and off-peak prices are changed. With these simplifications, \( \Delta W \) can be approximated by connecting the before and after consumption pairs \((\bar{x}_1, x_1 \text{ and } \bar{x}_2, x_2)\) with straight line demand.

![Diagram](image)

Fig. 1 -- Welfare gains from peak-load pricing
curves that incorporate the response to simultaneous adjustments of peak and off-peak prices. In the peak period, the welfare gain is the elimination of the distortion from pricing below marginal cost, given by area $T$. In the off-peak period, the gain is the increase in consumer surplus $U$ from increased consumption that is valued above its marginal cost. Letting $\Delta p = p_1 - \bar{p}$ and $\Delta x_i = x_i - x_i$, the total gain is approximately

$$\Delta W_a = T + U = -(1/2\Delta p_1 \Delta x_1 + 1/2\Delta p_2 \Delta x_2). \quad (3)$$

These calculations are summarized in Table 1.

An exact evaluation of $\Delta W$ can be obtained by using the functional form of the demand equations $x_1(\hat{p}_1, \hat{p}_2)$, $x_2(\hat{p}_1, \hat{p}_2)$ and calculating the changes in consumers' surpluses that occur along a particular path $P$ of price changes from $(\bar{p}, \bar{p})$ to $(p_1, p_2)$:

$$\Delta CS_e = \int_P x_1(\hat{p}_1, \hat{p}_2) d\hat{p}_1. \quad (4)$$

When the change in producer's surplus is added, the exact measure of the total welfare gain is

$$\Delta W_e = \Delta CS_e + \Delta p_1 \bar{x}_1 + \Delta p_2 \bar{x}_2. \quad (5)$$

The value of the line integral $(4)$ in general depends on the path $P$ over which it is evaluated, so that $\Delta W_e$ does not provide a unique measure of the welfare change from varying more than one price. However, if each of the price changes has only a moderate effect on the welfare of the consumer, the value of the line integral will closely approximate the compensating variation in income that would make the consumer indifferent between the initial and final price pairs. $^8$

$^7$ See Turvey (1968).

$^8$ Willig (1979a).
Table 1
WELFARE CALCULATION FOR A CONSUMER WITH LINEAR DEMAND CURVES

<table>
<thead>
<tr>
<th>CONSUMER ($\Delta CS$)</th>
<th>PEAK PERIOD</th>
<th>OFF-PEAK PERIOD</th>
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<tr>
<td>$\Delta$ Surplus</td>
<td>$-\Delta p_1 x_1 + 1/2 \Delta p_1 \Delta x_1$</td>
<td>$-\Delta p_2 - 1/2 \Delta p_2 \Delta x_2$</td>
</tr>
<tr>
<td></td>
<td>$= -\Delta p_1 \bar{x}_1 - 1/2 \Delta p_1 \bar{x}_1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(area $\bar{p}_{p,ec}$)</td>
<td>(area $\bar{p}_{p,pgf}$)</td>
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| PRODUCER ($\Delta PS$) | |
|------------------------| |
| $\Delta$ revenue      | $p_1 x_1 - \bar{p} \bar{x}_1$ | $p_2 x_2 - \bar{p} \bar{x}_2$ |
| $- \Delta$ costs      | $- p_1 \Delta x_1$ | $- p_2 \Delta x_2$ |
|                        | $= \Delta p_1 \bar{x}_1$ | $= \Delta p_2 \bar{x}_2$ |

Net $\Delta W = \Delta CS + \Delta PS = -1/2 \Delta p_1 \Delta x_1 - 1/2 \Delta p_2 \Delta x_2$
(area $T$) (area $U$)

NOTE: $\Delta p_1 = p_1 - \bar{p}$
$\Delta x_1 = x_1 - \bar{x}_1$
Change in Bills

At the initial consumption levels the new rate structure will change the consumer's monthly bill (and the utility's revenues from him) by

\[ \Delta B_0 = \Delta PS = \Delta p_1 \bar{x}_1 + \Delta p_2 \bar{x}_2. \]  

(6)

After adjusting his consumption, the consumer's change in bill will be

\[ \Delta B = \Delta B_0 + p_1 \Delta x_1 + p_2 \Delta x_2. \]  

(7)

If the consumer is representative of the residential class, his percentage of total consumption that occurs during the peak period, \(100x_1/x\), will be the same as the percentage for the entire class. By Eq. (2), \(\bar{p}\) is determined by the class mean percentage, so at the initial consumption levels the representative consumer's bill will be unchanged by the new rates (\(\Delta B_0 = 0\)). Because he would pay an identical bill for the same amount of electricity, at those consumption quantities he is indifferent between the two rates. Therefore, the shifts in electricity use \(\Delta x_1, \Delta x_2\) that are induced by the new rate constitute an unambiguous improvement in the consumer's welfare.

For a representative consumer the welfare gain \(\Delta W\) can be decomposed into the reduction in the consumer's bill (\(-\Delta B\)) and the change in his consumer's surplus. Recall, first, that because this consumer has the same proportion of peak-period consumption as the residential class, his bill is unchanged by the prices \(p_1, p_2\) at the initial consumption levels \(\bar{x}_1, \bar{x}_2\). Next, consider the peak-period effects of reducing consumption from \(\bar{x}_1\) to \(x_1\). In Figure 1a the consumer's bill falls by the rectangular amount \(x_1 \bar{x}_1 \text{de}\), but he also sacrifices surplus in the trapezoidal amount \(x_1 \bar{x}_1 \text{ce}\). This leaves a net improvement in welfare of \(cde\) (area T); the representative consumer captures the welfare gain of reduced distortion. Finally, in the off-peak period, surplus increases by \(\bar{x}_2, x_2, fg\), but the bill increases by only \(\bar{x}_2 x_2 \text{fh}\) for a net gain in welfare of \(fg\) (area U).

For the producer, the accounts are simpler. At the initial consumption levels the shift from \(\bar{p}\) to \(p_1, p_2\) leaves the representative consumer's bill, and therefore the utility revenues, unchanged. The
changes in consumption $\Delta x_1, \Delta x_2$ result in changes in revenues, $p_1 \Delta x_1$ and $p_2 \Delta x_2$ that are just equal to the changes in costs, because the prices have been set equal to marginal costs. Thus the consumer reaps all of the welfare gains.

For the nonrepresentative customer—whose percentage of total consumption in the peak period differs from the percentage for the entire class—the $\Delta W$ calculations are the same; but there is a shift of revenue between the customer and the utility given by the value $\Delta B_0$, which may be positive or negative.

In general, for a given tariff the consumption changes and therefore the welfare gain for a particular customer $j$ is a function of his peak, off-peak, and cross elasticities of demand $(\eta_1, \eta_2, \eta_{12})$ and his initial peak and off-peak use $(\bar{x}_1, \bar{x}_2)$:

$$\Delta W^j = f(\eta_1, \eta_2, \eta_{12}, \bar{x}_1, \bar{x}_2).$$

Ideally, welfare would be maximized if the utility could identify the set $S$ of all customers for whom $\Delta W^j$ exceeds the metering costs and place them on TOD rates. In practice, the utility must define a subclass $S'$ of customers to be metered that only imperfectly corresponds to the set $S$.

On the producer's side, the financial and welfare effects of moving to TOD pricing depend on whether the price is set equal to marginal cost in each period. When $p_1$ is set equal to the long-run marginal cost of supply in period $i$ and the utility is operating with the mix of generating plants that minimize total cost, any increase in consumption in period $i$ will result in an increase in operating and capital costs that exactly offsets the increase in revenue. Increased fuel costs will be incurred immediately, and adjustments in the utility's plant expansion program will accelerate construction schedules and alter the revenues that must be set aside to finance construction.

If, contrary to our assumption, TOD prices are not set equal to long-run marginal costs, then even though those rates would yield the same revenue at initial consumption levels, the utility's financial
position will be altered by changes in consumption. The net effect will be determined by the difference between price and marginal cost multiplied by the change in consumption in each period.

For example, suppose that the off-peak price \( p_2 \) is set equal to short-run marginal running costs and \( p_1 \) is set to recover the balance of the utility's revenue requirement not collected by the customer charge. If capital replacement costs exceed the utility's historical investment costs, \( p_1 \) will be less than peak period long-run marginal cost. In this case the lower peak period consumption will save more in long-run costs than was lost from reduced revenue, and the welfare gain will exceed \( \Delta W \).

**THE RATE DESIGN PROBLEM**

The rate design problem for peak-load pricing in the residential class is the specification of the TOD subclass \( S \). The design problem, broadly speaking, involves three key considerations: (1) defining the welfare-efficient set \( S \), (2) possibly adjusting rates to redistribute costs between subclasses of residential subscribers, and (3) choosing between a voluntary and mandatory TOD rate. In each of the cases we discuss, we assume that the absolute response to peak-load prices increases with the consumer's total electricity consumption.

**Identical Consumers**

Suppose that consumers use the same percentage of peak-period electricity, have the same price elasticities of demand \( (\eta_1, \eta_2, \eta_{12}) \), and differ only in levels of total consumption \( x^j \). This is the prototype case analyzed above. For each consumer \( j \), both the changes in consumption in each period and the welfare gains from peak-load pricing are proportional to size:

\[
\Delta W^j = F(\eta_1, \eta_2, \eta_{12}) \cdot x^j. \tag{9}
\]
Demand elasticities can be estimated from an experimental sample of the residential class. It is then possible to calculate critical size \( x^* \) at which the welfare gain is just equal to the metering cost. The appropriate subclass for peak-load rates is the set of all customers with total consumption greater than \( x^* \)—i.e., \( S = \{j | x_j > x^* \} \).

By assumption, all consumers have the same proportion of peak use, so at unchanged consumption levels no consumer's bill will rise if they are shifted to TOD rates. If the TOD plan is voluntary and includes a charge for the cost of the meter, it will attract just those consumers in the set \( S \). After the shift to TOD rates, each subclass pays revenues that cover all of its marginal costs.

**Relative Peak Period Consumption and Size**

Suppose that at a given level of total consumption consumers are identical, but that higher levels of consumption are associated with either an increasing or decreasing proportion of peak-period use. The welfare-efficient set \( S \) is again all consumers above a critical consumption level \( \hat{x} \). If the percentage of peak consumption increases with size, large consumers will face bill increases under TOD rates; and some consumers smaller than \( \hat{x} \) may be able to lower their bills by more than the cost of a meter. A mandatory plan for the set \( S \) would increase bills for TOD customers and, under a zero profit constraint, redistribute that revenue in the form of bill reductions to the remaining, smaller consumers on a uniform rate.\(^9\) However, a voluntary plan will fail to attract the efficient set of high consumption consumers and will incur the deadweight losses of low-response customers who enroll in order to benefit from lower bills.

Because of the assumed systematic relationship of peak consumption to total consumption, the mean marginal cost of supplying customers will vary directly with size (total consumption). If the percentage of peak consumption increases with size, the utility should consider a block rate structure with increasing marginal prices per kwh.

---

\(^9\)In principle, part or all of the revenue change could be returned to the set \( S \); see the discussion below on changes in equity vs. efficiency.
Within the class of time-undifferentiated rates, block rates will be more efficient than a uniform price \( p \) for all consumers. They will also be equitable in this case, ensuring that each customer pays an average price that is the appropriate combination of peak and off-peak marginal costs for his level of total consumption. If a block rate or other nonuniform price structure is used, then the welfare-efficient set of customers will face no bill increase in switching to TOD rates, and a voluntary plan will be effective.  

Heterogeneous Consumers

We now suppose that at any given level of total consumption, consumers have differing demand elasticities, differing relative peak period consumption, or both.

**Heterogeneous Demand Elasticities.** Suppose consumers have differing responses to peak and off-peak prices, because of their appliances, income, tastes, etc. The welfare-efficient set \( S \) includes all consumers at a given consumption level \( x \) with greater than a critical set of peak and off-peak elasticities \( \eta^*(x) \). For example, consumers with swimming pools or electric water heaters may be highly elastic and would generate net welfare gains even at quite low total consumption levels. At higher consumption levels it is efficient to include increasingly inelastic consumers. In practice, identification of differential elasticities would require the use of readily observed proxy variables such as the consumer's possession of a particular type of electrical equipment.

\[10\] Other types of time-undifferentiated rates could also be considered. For example, the basic rate structure could consist of a kilowatt (maximum demand) rate and a kilowatt-hour (energy) rate. If high annual consumer load factors (annual hours of utilization per kilowatt) are systematically associated with lower proportions of peak period use, a series of optional kilowatt/kilowatt-hour rates can closely approximate the mean marginal cost of supplying different customers. Electricité de France controls the circuit breakers of residential customers and uses this type of rate structure, levying charges for contractual maximum demand based on the rated capacity of the household circuit breaker. See Mitchell, Manning, and Acton (1978, Ch. 4).
Provided that differing elasticities are not associated with varying proportions of peak-period consumption, a shift to TOD rates will be bill-neutral for any customer. Under a voluntary plan that includes an additional charge equal to the metering cost, self-selection will define the efficient subclass $S$.

**Heterogeneous Relative Peak-Period Consumption.** When consumers at the same level of total consumption have varying proportions of on-peak use but all have the same elasticities, the critical size defining the welfare-efficient set $S$ depends on the proportion of peak use. Unless the peak and off-peak elasticities are quite different, however, the critical size is nearly the same with identical proportions of peak use. Consumers with higher than average peak-period use will face bill increases from TOD rates and would therefore not join the subclass under a voluntary plan. Consumers with lower-than-average peak use would join and enjoy bill reductions. This systematic self-selection would reduce the average revenue collected from the TOD subclass and require an offsetting increase in the uniform rate.

**Heterogeneous Elasticities and Heterogeneous Relative Peak-Period Consumption.** This is the general case, in which the welfare-efficient subclass depends on the customer's consumption, his elasticities, and his proportion of peak-period consumption. If peak-period proportions vary widely, a uniform rate results in significant cost averaging over high- and low-cost consumers. Mandatory TOD rates for the efficient subclass would result in both increases and decreases in individual bills, but this would be consistent with a principle of equity based on cost causation. However, under a voluntary plan the potential welfare gains would be diluted by significant self-selection of two sorts: (1) consumers with high peak use would remain on uniform rates, and (2) consumers with below average peak use and low elasticities would choose TOD rates.

**TOD Rates and Equity**

Assuming that the utility initially charges every customer a uniform $p$ for total kilowatt-hour consumption, we consider first a mandatory TOD plan.
If TOD meters were costless, a switch to TOD rates would be Pareto optimal and efficient for the entire system. Each consumer would then pay the exact marginal costs of his consumption. Bills would go up for consumers with higher than average peak-period consumption, and they would go down for consumers with lower than average peak consumption. In principle, the gainers could compensate the losers, leaving the net welfare gains to be shared in some fashion by all consumers. But in this cost-free situation, there is a strong presumption that the TOD rates are equitable, even without the compensation, and it costs nothing to achieve this result.\footnote{11}

When meters are costly, the shift to peak-load pricing itself consumes resources. Net gains in welfare are possible only for the sub-class of consumers who make sufficient changes in consumption to repay the metering investment. If there are no bill changes for the welfare-efficient subclass at unchanged consumption levels, then the introduction of TOD rates will not affect other residential customers. The gainers will be limited to the members of the TOD subclass.

However, if the shift to TOD rates based on marginal costs causes increases in the bills of the subclass, it is because the cost of serving those customers is higher than the class average. Assuming that the utility's profits are not increased, the switch to TOD rates must result in gains (i.e., bill reductions) for other residential consumers. In this instance, the introduction of a new pricing technology has made it possible to align consumers' bills more closely with costs, but the group subject to the new technology is made worse off.

Thus a classic conflict emerges: Shifting to TOD rates allows net increases in welfare, but this change will often redistribute costs. In terms of cost causation, the new distribution of costs may be equitable, yet because it increases the costs to some consumers it may be regarded as unjust.

\footnote{11 This concept is one of "anonymous equity"--the result of the change in pricing policy is assessed only in terms of the consumption characteristics of the consumer. A "targeted equity" approach would consider the identity of the consumer--his income, residence, race, age, or whatever (see Willig, 1979b).}
In practice, new rates may be possible only if the gainers pay some compensation to the losers. The available mechanism for compensation is an adjustment in the prices $\bar{p}$, $p_1$, and $p_2$.\textsuperscript{12} For example, if the switch to TOD rates would raise bills of the TOD subclass, then $p_1$ or $p_2$ must be reduced and $\bar{p}$ raised to avoid revenue shifts. The no-redistribution requirement further constrains the feasible prices, and at least one price must now deviate from marginal cost. The optimal TOD rates that are consistent with this constraint will minimize the distortions introduced into consumption in the two periods.

If a voluntary TOD plan is used, then all of the self-selected subclass will gain. If their peak-period proportion of consumption was previously at the class average, no change in other customers' bills is necessary. But, in general, the voluntary class will include below-average customers who enjoy bill reductions, and their switch to TOD rates will require some increase in the uniform rate $\bar{p}$ charged to other customers. To compensate these losers—the standard residential customers—the utility can raise $p_1$ or $p_2$ above marginal costs or charge an entry price for the TOD rate that exceeds the cost of the meter.

In both mandatory and voluntary plans, compensation of losers by gainers is purchased at the cost of efficiency gains that could otherwise be realized. This cost is the distortion that results when one or more prices diverges from marginal cost.

\textsuperscript{12}A change in the uniform entry fee will result in the correct compensation at only one level of total consumption.
III. ILLUSTRATIVE WELFARE ANALYSIS USING EXPERIMENTALLY MEASURED DEMAND ELASTICITIES

We use data derived from the Los Angeles Electricity Rate Study, a voluntary social experiment in peak-load pricing of electricity for residential customers. A total of 2689 households completed a baseline survey before enrollment. These households provide a cross-section of demographic information for the city. Approximately 1800 households were enrolled on one of 40 different experimental time-of-day, seasonal, or time-invariant electricity tariffs. The approximately 1000 households on TOD rates faced peak prices between 3 and 12 hours per day 5 or 7 days per week. Prices ranged from 5¢ to 13¢/kwh during peak hours and were either 1¢ or 2¢/kwh during off-peak hours. An additional 800 households faced either seasonal or time-invariant tariffs and paid prices from 2¢ to 8¢/kwh. The design of these experimental tariffs permits identification and estimation of the full set of own- and cross-price elasticities of demand for each TOD period. Finally, approximately 200 "control" households constituting a conventionally sampled load study were billed on the standard declining-block rate structure in effect for all nonexperimental residential customers in Los Angeles.

The experimental households were enrolled for a 30-month period, with the first families joining the study during the summer of 1976. Extensive demographic, economic, and attitudinal data were obtained through household interviews at the beginning, mid-point, and conclusion of the study.

CHARACTERISTICS OF THE SAMPLE AND THE LOS ANGELES SYSTEM

The present analysis is confined to the approximately 1400 households whose electricity use is monitored and recorded on magnetic

13"Time-invariant" rates are the same all hours of the year. Initial analysis of the seasonal and time-invariant tariffs is found in Lillard and Acton (forthcoming).

14For an overview of the purpose and major features of the study, see Acton, Manning, and Mitchell (1977). A more detailed account of the statistical design is found in Manning, Mitchell, and Acton (1979).
tape every 15 minutes. Two subgroups are examined separately for the welfare analysis. First, 390 households on time-invariant tariffs (including the 200 "control" households) were observed for the years 1977 and 1978 and used to determine the hourly patterns of use under conventional rate structures. Second, data from some 1148 households with cassette meters have been used to estimate own- and cross-price elasticities of demand by hour of day for a variety of TOD tariffs that could approximate long-run marginal costs in the Los Angeles system.

Mean use for the system is a little below 400 kwh/month in Los Angeles. The distribution of residential customers and use are displayed in Table 2. The pattern is skewed to the high end; the top 10 percent of the households (above 800 kwh per month) account for almost 30 percent of residential consumption. Households in the experimental sample were selected to be representative of the Los Angeles system, but higher levels of use were over-sampled to increase the statistical precision of the estimates. Mean use for the approximately 1148 experimental households is 585 kwh/month.

As indicated in the previous section, utility ratemakers frequently want a fairly simple procedure for identifying a subclass of residential customers for new TOD rate structures. One of the most convenient indicators is the level of electricity use. We examined the relationship between total monthly use and percentage of electricity consumed in different peak periods in the time-invariant sample. Averaged over two years, the data show a small increase in the proportion of energy used during peak hours as total consumption of electricity

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15 The 200 customer load study sample was drawn by the Los Angeles Department of Water and Power before the experiment began. The 190 households on time-invariant experimental tariffs were selected by Rand using stratified random sampling and the optimality routines developed by Conlisk and Watts (1969) and Morris (1976); see Manning, Mitchell, and Acton (1979). Electricity use during peak periods for the two samples was within one percentage point at every level of use.

16 These include 1047 households with TOD rates plus 101 households facing the same price per kwh year around.

Table 2
DISTRIBUTION OF 1 MILLION RESIDENTIAL CUSTOMERS
IN LOS ANGELES SYSTEM, 1978

<table>
<thead>
<tr>
<th>Stratum of Household Consumption (kwh/mo)</th>
<th>Average Consumption (kwh/mo)</th>
<th>Customers Percent</th>
<th>Cumulative Percent</th>
<th>Use Percent</th>
<th>Cumulative Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-200</td>
<td>127</td>
<td>30.0</td>
<td>30.0</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>201-400</td>
<td>291</td>
<td>36.1</td>
<td>66.1</td>
<td>26.8</td>
<td>36.6</td>
</tr>
<tr>
<td>401-500</td>
<td>447</td>
<td>10.4</td>
<td>76.5</td>
<td>11.9</td>
<td>48.5</td>
</tr>
<tr>
<td>501-600</td>
<td>547</td>
<td>6.8</td>
<td>83.3</td>
<td>9.5</td>
<td>58.0</td>
</tr>
<tr>
<td>601-700</td>
<td>647</td>
<td>4.5</td>
<td>87.8</td>
<td>7.4</td>
<td>65.4</td>
</tr>
<tr>
<td>701-800</td>
<td>747</td>
<td>3.1</td>
<td>90.9</td>
<td>5.8</td>
<td>71.2</td>
</tr>
<tr>
<td>801-900</td>
<td>848</td>
<td>2.1</td>
<td>93.0</td>
<td>4.7</td>
<td>75.9</td>
</tr>
<tr>
<td>901-1000</td>
<td>948</td>
<td>1.6</td>
<td>94.6</td>
<td>3.8</td>
<td>79.7</td>
</tr>
<tr>
<td>1001-1100</td>
<td>1048</td>
<td>1.1</td>
<td>95.7</td>
<td>3.1</td>
<td>82.8</td>
</tr>
<tr>
<td>1101-1200</td>
<td>1148</td>
<td>0.9</td>
<td>96.6</td>
<td>2.6</td>
<td>85.4</td>
</tr>
<tr>
<td>1201-1300</td>
<td>1248</td>
<td>0.7</td>
<td>97.3</td>
<td>2.3</td>
<td>87.7</td>
</tr>
<tr>
<td>1301-1400</td>
<td>1348</td>
<td>0.6</td>
<td>97.9</td>
<td>1.9</td>
<td>89.6</td>
</tr>
<tr>
<td>1401-1500</td>
<td>1448</td>
<td>0.4</td>
<td>98.3</td>
<td>1.6</td>
<td>91.2</td>
</tr>
<tr>
<td>1501-2000</td>
<td>1701</td>
<td>1.1</td>
<td>99.4</td>
<td>4.8</td>
<td>96.0</td>
</tr>
<tr>
<td>2001-2500</td>
<td>2204</td>
<td>0.4</td>
<td>99.8</td>
<td>1.9</td>
<td>97.9</td>
</tr>
<tr>
<td>2501+</td>
<td>3449</td>
<td>0.2</td>
<td>100.0</td>
<td>2.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>
increases. For example, in the period from noon to 9 p.m., Monday through Friday, percentage on-peak use increases from about 31 percent at low levels of use to almost 35 percent at higher levels. When use is disaggregated by season of the year, a clear pattern of peakness emerges in the summer months. During June, July, and August, percentage on-peak for the same 9-hour period increases from about 33 percent at low levels of use to almost 40 percent at the highest levels. A less pronounced pattern is observed in the fall when Los Angeles temperatures are frequently high.

These patterns reflect the role of air conditioning and perhaps swimming pool pumps, which are proportionately more important at higher levels of consumption, whose use coincides with many of the peak hours of the day. During the cooler seasons of the year, little relationship between level of use and proportion of peak is found, reflecting in part the very minor role of electric space and water heating in Los Angeles.

PRICE RESPONSIVENESS BY LEVEL OF USE

The welfare calculations require knowledge of the slopes of demand curves in peak and off-peak periods, net of any cross-price effects. The Los Angeles Electricity Rate Study was designed to provide data from which to make such estimates for a wide variety of potentially relevant pricing periods and price levels. In this paper we rely on single-equation estimates of demand curves for six pricing periods. The periods and typical percentage of total consumption are:

<table>
<thead>
<tr>
<th>Period</th>
<th>Hours</th>
<th>% of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9 a.m. - noon, Monday-Friday</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>noon - 3 p.m., Monday-Friday</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>3 p.m. - 6 p.m., Monday-Friday</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>6 p.m. - 9 p.m., Monday-Friday</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>9 p.m. - 9 a.m., Monday-Friday</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>Saturday &amp; Sunday</td>
<td>29</td>
</tr>
</tbody>
</table>
As the selection of the model and testing of alternative variable transformations is a major undertaking, we will sketch the essential features of the model and report the principal effects needed for present analysis.\textsuperscript{18} The specification for electricity use in the five weekday periods includes own- and cross-prices in each of the five daily periods. Specification of total weekend use contains only the weekend price and is estimated by ordinary least squares.\textsuperscript{19}

Model of TOD Electricity Demand

The TOD demand estimates are based on a variance components model of electricity use by period of the day during the first 18 experimental months for approximately 1100 households.\textsuperscript{20} The general specification for weekday electricity use in time period $i$ is

$$\ln K_i = f(P_1, \ldots P_5; DZ, Z, X)$$

$$= a_{10} + \sum_{j=1}^{5} a_{ij} \ln P_j + \sum_{i=1}^{4} b_{ij} \ln P_i DZ_j + \sum_{i=1}^{4} c_{ij} \ln P_i \ln Z_j + \sum_{i=1}^{4} d_{ij} \ln Z_i + e_{ij} X_j,$$

where

- $K_i$ = daily kwh consumed in period $i$,
- $P_j$ = price in period $j$,
- $DZ_j$ is a variable for each of four types of electricity-using equipment (air conditioning, electric space heating, swimming pools, and all other appliances that are not sensitive to weather),

\textsuperscript{18}Detailed analysis of the demand estimates will be found in Manning and Acton (forthcoming).

\textsuperscript{19}Because the TOD tariff analyzed below has a uniform off-peak price throughout the weekend, the sample computation for weekend regressions contained all experimental households that face an off-peak price on weekends (about half of the TOD households) as well as 101 households on time-invariant rates whose use is monitored by tape cassettes for a total sample of 620.

\textsuperscript{20}A total of 30 experimental months will eventually be available for analysis; the estimated demand equations used here are preliminary and subject to refinement. Estimation of a simultaneous system of demand equations, when developed, may also affect the parameter estimates.
$Z_j$ is an index value (in kwh) of the four types of electricity-using equipment, and
$X_j$ is all other explanatory variables.

All variables (except dummy variables) are expressed in natural logarithms and their definition is given in Table 3. Selection of this double logarithmic specification, following extensive examination of alternative variable transformations, achieved well-behaved and unbiased estimates and test statistics. We also tested a variety of price interactions before we arrived at the final specification; the ones selected were all significant by an F test.

**Explanatory Variables**

Our basic measure of bill effects and change in welfare result from our comparing a reference pattern of demand for electricity with the pattern predicted under alternative tariffs. Changes in price levels drive this calculation. If the effect of price on consumption were additively separable from the effect of other explanatory variables, then we could make the welfare calculations using only price coefficients; nonprice variables would drop out in the differencing. However, in the logarithmic specification of the demand equations, prices interact strongly with appliance and pool size variables. Consequently, the changing values of the explanatory variables by level of total consumption will affect the welfare and bill calculations.

Table 4 shows the mean values of selected appliance variables for the year preceding the study for 2689 households stratified by the level of monthly consumption in that year. Most of these variables increase with level of use and result in higher price elasticities at high levels of monthly consumption. For example, less than 10 percent of households at low levels of use have

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See Manning and Acton (forthcoming).
Table 3
DEFINITIONS OF VARIABLES IN ESTIMATED DEMAND EQUATIONS

DEPENDENT VARIABLE

\[ K_i = \text{daily kwh in period } i. \]

INDEPENDENT VARIABLES

\[ P_j = \text{price in period } j; \]

\[ Z_1 = 0 \text{ if no air conditioning; otherwise,} \]
\[ = \ln \text{ROOMS} \cdot \ln (\text{AC} \cdot \text{CDH}), \]

where

\[ \text{AC} = \sum_{i} A_i \text{ for four air conditioning appliances,} \]

\[ \text{CDH} = \text{cooling degree hours measured as deviations from 65°F;} \]

\[ Z_2 = 0 \text{ if no HEAT; otherwise} \]
\[ = \ln \text{ROOMS} \cdot \ln (\text{HEAT} \cdot \text{HDH}) \]

where

\[ \text{HEAT} = \text{electric space heating, and HDH} = \text{heating degree hours measured from 65°F;} \]

\[ Z_3 = 0 \text{ if no swimming pool; otherwise,} \]
\[ = \ln (\text{length times width of swimming pool}); \text{ and} \]

\[ Z_4 = \ln \sum_{i} A_i \text{ for all other appliances,} \]

where

\[ A_i = \text{count of appliance } i \text{ in the household and} \]

\[ \gamma_j = \text{average kwh for appliance } j. \]

---

\[ ^a \text{Values of } \gamma_i \text{ for principal climate control appliances (in kwh/mo.) are:} \]

refigerative central air conditioner (328), evaporative central air conditioner (120),
refrigerative window air conditioner (60), and evaporative window air conditioner (40).
Weights were developed by the Edison Electric Institute and adapted to Los Angeles conditions by DWP engineers.

\[ ^b \text{Values of } \gamma_i \text{ for non-climate appliances are: refrigerator (52),} \]

frostfree refrigerator (106), dishwasher (25), gas clothes dryer (8),
electric clothes dryer (72), clothes washer (8), electric water heater (333), electric stove (87), and television (30).
Table 4

DISTRIBUTION OF SELECTED EXPLANATORY VARIABLES BY LEVEL OF USE

(Mean value of variables, N = 2689)

<table>
<thead>
<tr>
<th>Household Consumption (kwh/mo)</th>
<th>Index of Selected Appliances, APPLα (kwh/mo)</th>
<th>Electric Space Heating (%)</th>
<th>Air Conditioner, Indexb (kwh/mo)</th>
<th>Swimming Pools</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-200</td>
<td>118</td>
<td>3</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>201-400</td>
<td>202</td>
<td>8</td>
<td>57</td>
<td>1</td>
</tr>
<tr>
<td>401-500</td>
<td>251</td>
<td>6</td>
<td>61</td>
<td>4</td>
</tr>
<tr>
<td>501-600</td>
<td>289</td>
<td>11</td>
<td>95</td>
<td>9</td>
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<tr>
<td>601-700</td>
<td>316</td>
<td>9</td>
<td>123</td>
<td>14</td>
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<tr>
<td>701-800</td>
<td>334</td>
<td>9</td>
<td>144</td>
<td>25</td>
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<tr>
<td>801-900</td>
<td>327</td>
<td>3</td>
<td>156</td>
<td>43</td>
</tr>
<tr>
<td>901-1000</td>
<td>360</td>
<td>12</td>
<td>159</td>
<td>37</td>
</tr>
<tr>
<td>1001-1100</td>
<td>362</td>
<td>8</td>
<td>187</td>
<td>53</td>
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<tr>
<td>1101-1200</td>
<td>381</td>
<td>10</td>
<td>191</td>
<td>69</td>
</tr>
<tr>
<td>1201-1300</td>
<td>385</td>
<td>9</td>
<td>163</td>
<td>65</td>
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<tr>
<td>1301-1400</td>
<td>410</td>
<td>0</td>
<td>204</td>
<td>61</td>
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<tr>
<td>1401-1500</td>
<td>406</td>
<td>7</td>
<td>222</td>
<td>79</td>
</tr>
<tr>
<td>1501-2000</td>
<td>441</td>
<td>14</td>
<td>237</td>
<td>80</td>
</tr>
<tr>
<td>2001-2500</td>
<td>492</td>
<td>31</td>
<td>283</td>
<td>80</td>
</tr>
<tr>
<td>2501+</td>
<td>510</td>
<td>10</td>
<td>352</td>
<td>80</td>
</tr>
</tbody>
</table>

αPercent of households with each type of appliance, weighted by mean use in Los Angeles.

bPercent of households with each type of air conditioner, weighted by mean use in Los Angeles.
swimming pools in Los Angeles, whereas about 80 percent of the households consuming more than 1300 kwh/month have a pool. Moreover, the average size of a pool also increases with higher levels of use. In the estimated demand equations, both the presence of a swimming pool and its size affect the TOD price elasticities. The air conditioning and appliance variables also increase systematically with level of use and increase elasticities at higher levels of use.

Own-Price Elasticities

Manning and Acton explore several alternative specifications and find negative own-price elasticities for households on experimental TOD rates. The estimated cross-price effects are, for the most part, positive with modest statistical significance. For the present analysis, we selected the specification outlined in Eq. (10) on the basis of the general robustness of its price coefficients and accuracy of predictions throughout the range of data. Table 5 presents own-price elasticities in the five distinct weekday pricing periods. For each level of usage, k, these values, giving the elasticity of consumption in period i with respect to the price in that period, are calculated from the coefficients in Eq. (10) as

\[ \eta_{ik}^{own} = a_{ii} + b_{ii} + \sum_{j=1}^{4} c_{ij} \bar{Z}_{jk} + \sum_{j=1}^{4} c_{ij} \bar{Z}_{jk} \]

where a typical value of \( \bar{Z}_{jk} \) is \( \bar{Z}_{ik} = \ln \text{ROOMS}_k \cdot \ln(\text{AC}_k \cdot \text{CDH}_k) \).

The values in Table 5 show average price responsiveness by level of use for the sample as a whole. Households at the lowest levels of use are quite inelastic, with own-price elasticities varying from less than -1 percent to almost -9 percent in the daytime periods. Own-price elasticities increase systematically with level of use during daylight hours, with the greatest price elasticity around -40 percent found in

\[22\] On average, a pool pump uses about 300 kwh/month, so it is almost impossible for households using an annual level less than 400 kwh/month to have a pool unless it is very small or used only for brief periods during the year.
Table 5
OWN-PRICE ELASTICITIES FOR WEEKDAY ELECTRICITY
USE BY LEVEL OF USE

<table>
<thead>
<tr>
<th>Household Consumption (kwh/mo)</th>
<th>Period of Day</th>
<th>9-Noon</th>
<th>3 p.m.</th>
<th>6 p.m.</th>
<th>9 p.m.</th>
<th>9 a.m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-200</td>
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</table>

Households with Pools<sup>a</sup>

| 1001-1100 | -.328 | -.395 | -.235 | -.189 | -.135 |

<sup>a</sup>Calculated at mean value of all nonpool explanatory variables for one stratum of use. Mean pool size for households having pools is used in each stratum prediction.
the group using 2001-2500 kwh per month. During the daytime, own-price elasticities are generally largest in late morning and early afternoon and are typically about half the midday value during the period 6 p.m.-9 p.m. Overnight own-price elasticities are generally small and insensitive to levels of use.

The presence of a swimming pool increases price elasticity at all levels of use. If we hold all other household characteristics constant for a given stratum of use, adding a swimming pool (with mean SIZE for that stratum) increases price elasticities to between -30 and -46 percent during the hours 9 a.m.-noon and noon-3 p.m. Even during the periods 3 p.m.-9 p.m., elasticities generally are between -13 and -17 percent at lower levels of use and -22 to -32 percent at higher levels. Overnight elasticities for the swimming pool population are about half the daytime elasticities. Table 5 shows a comparative set of elasticities for households with pools in the 1001-1100 consumption stratum.

The markedly higher proportional price responsiveness occasioned by a swimming pool, combined with the higher level of use indicates that TOD rates may be effective for swimming pool households. Furthermore, the prevalence of swimming pools at high levels of use means that a utility system with an important swimming pool load can sort out a large fraction of its potentially responsive customers by using the convenient indicator of average monthly electricity consumption.

Because household response to time-of-day rates includes cross-price as well as own-price effects, the percentage change in consumption under a TOD tariff is a function of the entire vector of peak and off-peak prices. To summarize this responsiveness in single measures, we define the peak tariff elasticity when shifting from a flat rate to a particular TOD rate to be the percentage change in the peak consumption divided by the percentage change in the peak price. The off-peak tariff elasticity is defined similarly. The welfare calculations reported below are based on these tariff elasticities and thus include cross-price as well as own-price responsiveness.
WELFARE GAINS AND BILL CHANGES

We evaluate alternative tariffs in terms of the net change in welfare and the redistribution of costs. The summary measure $\Delta W$, developed in Section II, captures the effects of changes in economic efficiency and consumer welfare. These gains are compared with any lump-sum costs of a more complicated tariff structure. Changes in customers' bills are central to the redistributive effects of any new tariff and will determine the likelihood of a tariff being accepted on an optional basis. In general, the introduction of TOD prices will raise the bills of some households and lower the bills of others—although there will not necessarily be a simple relationship between these changes and level of use.

An Illustrative TOD Tariff

We assume for this analysis that the utility initially has a time-invariant tariff in effect with a reference price of 5¢/kwh (given by Eq. (2)) that is based on a weighted average of long-run marginal costs. System load curves in Los Angeles and many U.S. utilities show a broad daytime peak load. To reflect this condition we define the peak pricing period to be noon-9 p.m., Monday through Friday and find that 33 percent of all electricity consumed by the residential load sample occurs during these hours. Assuming a marginal cost and price of 3¢/kwh in the off-peak period, a peak-period price of 9¢/kwh would yield the same revenue as the time-invariant tariff if applied to the entire residential class. This illustrative tariff is similar to a low-voltage tariff presently available in Los Angeles to some residential customers. That rate was designed to be consistent with TOD rates at high voltages, and is

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The assumption of two pricing periods, each with constant marginal costs and uniform loads, is in the spirit of the basic Steiner peak-load pricing model. A more detailed and realistic examination would reveal a smoothly varying system load curve and marginal costs that vary continuously over time. Nevertheless, for residential customers the feasible rate structure will probably be limited to a maximum of two (or at most three) distinct prices, and our calculations are intended to illustrate the approximate welfare gains that could be achieved in those circumstances.
Table 6
EFFECTS OF AN ILLUSTRATIVE TOD TARIFF—ALL HOUSEHOLDS

<table>
<thead>
<tr>
<th>Household Consumption (kwh/mo)</th>
<th>Change in Bill at Initial Use</th>
<th>Tariff Elasticities(^a)</th>
<th>Total Change in Bill ($/mo)</th>
<th>Change in Welfare ($/mo)</th>
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<td>(\Delta B_0)</td>
<td>Peak (%)</td>
<td>Off-Peak (%)</td>
<td>(\Delta B)</td>
</tr>
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<td></td>
<td>$/mo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>(3)</td>
<td>(4)</td>
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\(^a\)Tariff elasticity in period 1 is defined as \((\Delta Q_1/Q_0)/(\Delta p_1/p)\), where \(p_1\) is the new price in period 1 measured against a change from \(p\) (5c in this case) and \(\Delta Q_1\) reflects the full adjustment to own and cross-prices; negative values indicate reduced (increased) use when price rises (falls).
based on an assessment of system marginal costs subject to an overall revenue constraint. 24

Column 1 of Table 6 shows the changes in bills at the initial levels of consumption. Based on the proportion of peak and off-peak use in our data, the $\Delta B_0$ calculation shows generally increased rates at all levels of use, although the changes are small. The responses to peak and off-peak rates are summarized in cols. 2 and 3 in terms of the tariff elasticities. These elasticities increase in absolute value from a few percentage points to about 12 percent in the peak period and from about 12 to 20 percent in the off-peak hours. Column 4 shows that changes in peak-period use fall more than in proportion to increased total use and range from a few kwh/month to over 100 at the highest levels of use.

These responses, when combined with the effect of the new rates at the original consumption levels, result in the total change in the monthly bill, $\Delta B$, in col. 5. Customers using less than 500 kwh/month are predicted to have small increases in total monthly bills. For larger customers, the net result is a decrease in monthly bills.

The final column shows two measures of the change in consumer and producer welfare, $\Delta W$. Exact calculation 25 of the welfare change $\Delta W$ produces a somewhat larger gain than the linear approximation $\Delta W$. Welfare increases steadily with size of use, and the magnitudes of the change are modest at the lowest levels of use. Average welfare gains by the exact measure do not reach $1 per month until consumption exceeds 800 kwh/month. In Los Angeles, slightly over 9 percent of the residential customers use this much electricity.

Metering Costs

A social benefit-cost evaluation of TOD rates must compare the expected welfare gains with the cost of a more complex tariff. Residential customers will almost always require new meters, which today

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24 See Mayor's Blue Ribbon Committee on Water and Power Rates (1977).

25 The path over which the line integral $\Delta W$ was evaluated was obtained by successively changing $p_1$, then $p_2$, ..., $p_6$ from their initial 5c value to the peak (9c) and off-peak (3c) prices.
cost between $80 and $160, depending on particular features. However, large-scale U.S. production of time-of-day meters might substantially reduce the price, particularly if computer chip technology were applied.

For illustrative purposes, we assume an installed cost per meter of $150. With a 15-year life and an 8 percent real interest rate, this amounts to a monthly cost of $1.42. At that cost, time-of-day pricing should be applied to only a fraction of households to achieve efficiency gains; net increases in welfare resulting from changes in utilization of existing appliances are predicted for customers over 1100 kwh/month. In the Los Angeles system, although only 4.3 percent of the households use over 1100 kwh/per month on average, they account for over 17 percent of residential consumption. As a consequence, the utility system can consider placing a limited number of households on TOD rates and still affect a significant amount of electricity consumption. Of course, for some individuals at lower levels of use who have above-average price responsiveness, net welfare gains would also be positive.

Results

How well would the illustrative TOD tariff work if it were offered on a voluntary basis? The welfare-efficient set S includes (on average) all households above 1100 kwh/month. But, at initial consumption levels, on average, households in all but the largest stratum would expect an increase in bills if they were charged $1.42 for the monthly cost of a TOD meter to obtain the rate. Unless households could shift their time patterns of electricity use, a voluntary plan would fail to attract the set S. In this instance, even issuing an advisory bill (based on present use but calculated at TOD prices) will not help to attract customers; it will only confirm that $\Delta B_0$ does not offset the extra charge for metering.

Because of their considerably higher tariff elasticities, households with swimming pools benefit from time-of-day pricing at almost all levels of use (Table 7). All households using more than 500 kwh/month are predicted to receive bill decreases ($\Delta B$) after adjusting use under the illustrative TOD rate, and net welfare gains exceed the assumed cost of metering at 800 kwh/month. However, at unchanged
### Table 7
 EFFECTS OF AN ILLUSTRATIVE TOD TARIFF—HOUSEHOLDS WITH POOL

<table>
<thead>
<tr>
<th>Household Consumption (kwh/mo)</th>
<th>Change in Bill at Initial Use ($/mo)</th>
<th>Tariff Elasticities&lt;sup&gt;a&lt;/sup&gt;</th>
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<td></td>
<td>$\Delta B_0$</td>
<td>Peak (%)</td>
</tr>
<tr>
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<sup>a</sup>Tariff elasticity in period i is defined as $(\Delta q_i / q_i) / (\Delta p_i / p)$, where $p_i$ is the new price in period i against a change from $p$ (5c in this case); negative values indicate reduced (increased) use when price rises (falls).
consumption, households with swimming pools would expect increased bil
s at every level of use if they had to pay for meters. Although this bill increa
se is more than offset by changes in the time pattern of consumption for the majority of households, a voluntary TOD plan for these customers might also encounter difficulties in attracting house-
holds.

Similar calculations show that households with electric space heatin
, in contrast to those with swimming pools, use a dispropor
tionate amount of electricity during off-peak hours. Consequently, these consumers would enjoy bill decreases ($\Delta B^D$ negative) at all levels of use, and the reduction exceeds metering costs above 600 kwh per month. Welfare gains are similar to those for the entire population and exceed metering costs only at the very highest levels of use (greater than 1100 kwh/month on average). However, in contrast to the two cases discussed above, a voluntary plan is likely to work for this subpopulation. In fact, it is likely to attract more than the welfare-efficient subgroup S because of the perceived bill reductions at lower levels of use. The policymaker is faced with the challenge of excluding a significant number of households if he wishes to confine TOD rates to a subclass of consumers for which improvements in efficiency can reasonably be expected.

**Long-Term Effects**

The elasticities used in these calculations have been estimated from data that reflect changes in electricity use during the first half of a 30-month experimental period. Although TOD rates offered participants financial incentives to modify the timing of their electricity consumption, the limited duration of the study was not a sufficient inducement for them to make significant alterations in major electricity-using appliances. Therefore, these use elasticities measure only a fraction of the total adjustment that would be expected from a permanent and widespread shift to residential TOD rates; consequently, the welfare calculations are conservative.

Permanent adoption of TOD rates could induce changes in appliance design and ownership and possibly a reduction in metering costs.
These developments would substantially enlarge the subclass of households for whom TOD rates would be effective. Even in these circumstances, however, time-of-day pricing will probably be appropriate for only a limited subgroup of U.S. residential consumers.
IV. CONCLUSION

Electricity supply is a classic instance of variation in marginal costs over time, produced by major variations over the day in total demand combined with large fixed costs of capacity. But to meter residential consumers and bill them under time-of-day rates is costly. Although TOD rates will encourage more efficient use of electricity, they will result in net welfare gains only if the value of changes in peak and off-peak use are sufficiently large.

Using data from the Los Angeles peak-load pricing experiment, we have estimated the responses of consumers to TOD rates at varying levels of monthly electricity use. By assuming that a tariff reflects a utility's long-run marginal costs and that a TOD meter costs $150, we have calculated changes in both net welfare and consumer bills. Although the actual magnitudes are only illustrative, the qualitative patterns found here should apply to many U.S. utilities. We find that TOD rates

- are not desirable for most residential customers on efficiency grounds;
- produce net welfare gains at lower total consumption levels for households with swimming pools;
- increase bills of most users who make no changes in consumption unless they have electric space heating;
- lower the bills of most electric space heating customers but improve net welfare only at levels of consumption exceeding 1100 kwh/month;
- produce net welfare gains in the residential class at levels of consumption exceeding 1100 kwh/month.

Widespread and permanent adoption of residential TOD rates would, over time, increase the amount of electricity shifted from peak-period use and lead to lower metering costs. These developments would expand
the subclass of residential consumers that can efficiently be billed under TOD rates.

The choice between a mandatory and a voluntary TOD rate is difficult. Price elasticities and welfare gains increase with the level of total consumption. Consequently, the utility could place all customers above a specified level of monthly consumption on mandatory time-of-day tariffs and achieve net gains in welfare. An optional TOD rate, offered to the same customers, would increase most bills at initial use levels but yield bill reductions and net welfare gains when responses in electricity use are taken into account. However, uncertain about their ability to reduce peak consumption, many customers may fail to select a TOD rate voluntarily even though they could benefit. Furthermore, at lower levels of use customers would seek an optional rate if their bills would be reduced, but their patterns of change would not justify the rate changes on efficiency grounds.

The difficulties of using a voluntary plan to introduce time-of-day rates leave the policymaker with two options: Either time-of-day rates can be made mandatory for the appropriate residential subclass, or the present standard rates can be converted to redesigned rate structures that will make optional time-of-day rates attractive for just those customers who realize net welfare gains by more accurately reflecting the average cost of that subclass. In the latter case the standard rates for the subgroup of customers with higher-than-average peak period consumption must be increased, either uniformly or possibly in the form of an increasing block rate structure. At the same time, if there is another group of consumers with lower-than-average peak period consumption, their standard rate should be reduced to prevent them from switching to the time-of-day rate merely because it will lower their bills.
REFERENCES


