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Optional Time-of-Use Prices for Electricity: econometric analysis of surplus and Pareto impacts

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ABSTRACT

We specify an econometric model of tariff choice and time-of-use (TOU) consumption under optional TOU tariffs. The specification is consistent with the theory of self-selecting tariffs, in that each customer's choice among tariffs is based on its demand parameters, which vary in the population. The model is estimated on data from a specially designed experiment under which the optional TOU rates varied over customers and the TOU consumption of customers who remained on standard rates was recorded. With the estimated model, we compare the TOU consumption and price elasticities of customers who chose TOU rates with those who chose standard rates. We also estimate the impact of the experimental TOU rates on consumer surplus and the utility's profits. The analysis suggests that, with one possible exception, the offering of the optional TOU rates did not Pareto dominate standard rates. However, total surplus, excluding measurement costs, is estimated to have risen by $1.41 to $2.55 per month per customer who chose the TOU rates. For measurement costs below these amounts, the optional TOU rates are therefore found to increase total welfare, with customers who chose the TOU rates gaining and shareholders and/or customers who did not choose the TOU rates being hurt. For higher measurement costs, the optional TOU rates cannot be justified on surplus grounds.

I. Introduction

Optional time-of-use (TOU) prices, under which the customer has a choice between TOU and standard, non-time-differentiated rates, are far more prevalent than mandatory TOU prices. Boiteux (1988) reports that of the seven European countries with TOU electricity rates for residences, six offer them on a voluntary basis. Aigner (1988) recounts a similar story for the U.S. where voluntary TOU electricity rates are becoming fairly widespread while mandatory TOU rates, in the residential sector at least, have been applied nearly exclusively in experiments of limited coverage and duration. In the commercial and industrial sectors, mandatory TOU rates for electricity are more common, though voluntary applications still outnumber mandatory ones.

The welfare implications and justification of optional TOU rates are different from those of mandatory TOU rates. Mandatory TOU rates are justified by marginal cost being different in different time periods, due usually to demand varying by TOU such that marginal cost is calculated on a different part of the cost curve. Welfare rises as prices in each time period are moved closed to marginal cost, and a welfare improvement is attained if the reduction in deadweight loss that occurs from moving toward marginal cost exceeds the cost of measuring consumption by TOU. Given that the measurement costs are indeed dominated, the first-best prices are those that equal marginal cost in each period, and the second-best prices (under the constraint that the provider break even) correspond to a type of Ramsey rule. The seminal work on mandatory TOU prices has been provided by Houthakker (1958), Boiteux (1960), and Williamson (1966).

Optional TOU prices cannot provide as much total surplus as mandatory TOU rates but have the potential advantage of being Pareto dominating. The lower surplus occurs because some customers choose standard rates when given a choice:[1] if, as presumed, the TOU rates are closer to marginal costs than the standard rates, then the customers that remain on standard rates cause a larger deadweight loss than they would if forced to consume under TOU rates.[2] Under fairly general conditions, however, MacKie-Mason (1990) and Train (1988) have shown that, given an existing standard rate, optional TOU rates can be designed that increase welfare compared to the standard rates alone, even in a situation in which the provider is required to break even. From a total welfare perspective, therefore, optional TOU rates can be used to increase welfare relative to a status quo of standard rates but not as much as would be possible with mandatory TOU rates.

Unlike mandatory TOU rates, optional TOU rates have the potential to Pareto dominate an existing situation that consists of standard rates only. A shift from standard rates to mandatory TOU rates hurts some customers, namely those with a large share of their consumption in the expensive "peak" period and sufficiently inelastic demand in each period. Under optional TOU rates, any customer who would be hurt by the TOU rates chooses to remain on the standard rates; consequently, no customer is hurt by the offering of optional TOU rates. The optional TOU rates Pareto dominate the original standard rates as long as the provider's profits do not decrease as a result of the offering. While arbitrarily defined optional TOU rates can either increase or decrease the provider's profits, it is necessarily possible, under fairly general conditions, to identify optional TOU rates that increase profits and hence Pareto dominate the offering of standard rates alone (MacKie-Mason, 1990; Train, 1988).[3] The gain in total welfare from a Pareto dominating optional TOU tariff might be small compared to the potential gain from mandatory TOU rates. The difference can be considered the "price" of Pareto dominance.

The prevalence of optional TOU rates can perhaps be attributed to their potential for Pareto dominance. Though regulators might not think in Pareto terms, Pareto dominance manifests itself in ways that are clearly evident and important to regulators: a lack of opposition to a change.[4] In contrast, attempts to shift from standard to mandatory TOU rates are often blocked by customers who would be hurt by the change.

Actually, the characteristic of optional TOU rates that makes them potentially Pareto dominating also explains and justifies their adoption when they do not Pareto dominate. An optional TOU tariff that increases total surplus but does not Pareto dominate helps some customers (those who choose it) and reduces profits. The lost profit is either spred over numerous shareholders or over numerous customers through higher general rate levels. Introducing optional TOU rates might therefore be politically feasible when a shift to mandatory TOU rates (which can induce large losses to a few customers) is not. From a regulatory perspective, the optional TOU rates to avoid are those that decrease total surplus. Unfortunately, the regulator is seldom in the position to determine whether this would occur. The model that we present below is intended to assist in this determination.

The design of optional TOU rates that increase welfare and perhaps even Pareto dominate an existing standard tariff requires knowledge of the distribution of demand parameters across customers. Under the behavioral theory of self-selecting tariffs (Faulhaber and Panzar, 1976; Brown and Sibley, 1986; Train, 1991), each customer evaluates the surplus that it attains under the rates schedules that are offered and chooses the tariff that provides the greatest surplus. Whether TOU rates offer greater surplus than standard rates to an individual customer depends on the level of demand and the same- and cross-price responsiveness of demand in each time period. Since customers sort themselves between tariffs on the basis of their demand parameters, the distribution of these parameters is relevant rather than simply the average parameters in the population. Two extreme cases will serve as illustration. Consider first a situation in which all customers are completely insensitive to price but differ in their consumption levels by TOU independent of price. In this case, each customer will choose the rate schedule under which its bill will be lower for its fixed consumption: the provider loses revenues compared to standard rates alone, but its costs remain the same. Pareto dominance is not attained, and, depending on how this loss is recouped, total welfare may fall. Consider now another case in which a group of customers are highly price responsive and, in fact, are able to shift all of their consumption to the low-cost period of the day (the "off-peak") without loss of welfare. A TOU schedule with only a small price difference across periods will be chosen by these customers. The provider will benefit since its costs will decrease more than its revenues; these increased profits can, depending on the form of regulation, be transferred to all customers through lower rates under both schedules.

While the distribution of demand parameters is necessary information for the appropriate design of optional TOU rates, previous empirical analysis has estimated only average parameters. Nearly all previous analyses of TOU demand have examined mandatory TOU rates, in which the distribution of parameters is not critical and the task is to estimate average price responses; see, for example, the articles edited by Lawrence and Aigner (1979) and Aigner (1984). Three studies have analyzed data from optional TOU rates. Of these, only Hausman and Trimble estimated a model that is consistent with the theory of self-selecting tariffs. Goett (1988) and Caves et al (1989) estimated regressions of TOU demand conditional on the customer's choice between TOU and standard tariff. To account for the endogeneity of price, the regressions include an inverse Mills ratio based on the probability of the customer choosing TOU rates (the approach developed by Heckman, 1979, and Dubin and McFadden, 1983). A binary choice model was estimated to obtain this variable. However, the specification of the choice model is independent of the demand equations and, in particular, does not relate the customer's choice of tariff to its demand parameters. This approach is adequate for examining the demand impacts of the particular TOU rates that were actually offered; however, it cannot be used to calculate changes in consumer surplus (since the utility function in the choice equation is inconsistent with the demand equations) or to examine the penetration and response to other TOU rates.

Econometric analysis of optional service options for telecommunications has progressed further in this regard. Cox (1988), Hobson and Spady (1988), and MacKie-Mason and Lawson (1993) specify models that link the customer's choice of service option to its parameters of usage demand, with these parameters varying in the population. We draw upon these models in our specification, and, insofar as possible, relate our empirical findings to theirs.[5]

In the sections that follow, we specify and estimate the model of customers' choice between TOU and standard rates and their TOU consumption conditional on this choice. The model is consistent with the theory of self-selecting tariffs in that each customer chooses the tariff that provides the greater surplus given the customer's demand parameters. Demand parameters vary in the population, and the moments of this distribution are subject to estimation. As such the model draws on the concepts of earlier analyses of varying-parameters models of tariffs choice and usage. The estimated model can be used to calculate the impacts of the tariffs that were offered as well as to forecast, for alternative optional TOU and standard rates, the proportion of customers choosing each tariff, the TOU consumption and surplus of customers, and the revenues of the provider.

The model is estimated on data from an specially designed experiment on optional TOU rates conducted by the Pacific Gas and Electric Company (PG&E). These are the same data that Goett analyzed; Caves et al examined data from an earlier phase of this same experiment.[6] The experiment offered different TOU rates to different customers and observed the TOU consumption of customers who chose the TOU rates as well as a sample of customers who chose to remain on the standard rates. Unlike data from a non-experimental setting, the TOU rates that were offered varied over customers, and the TOU consumption of customers under standard rates is known. Both of these elements enhance the ability of the econometrics to infer the underlying distribution of demand parameters. Nevertheless, high correlations among relevant variables allow only a restricted set of variances and covariances among parameters to be estimated. The level of customer heterogeneity that is allowed in the theoretical specification is considerably greater than could actually be estimated on our data.[7] Further work, including the construction of experiments designed with explicit recognition of the underlying behavioral/econometric model to be estimated, is needed to estimate the entire variance-covariance matrix.

The remainder of the paper is organized as follows. The model is specified in section II. The data are described in section III. The estimation procedure and results are given in section IV. Section V compares the TOU consumption and elasticities of customers who chose TOU tariffs with those who chose the standard tariff and calculates the impact of the experimental TOU tariffs on PG&E's profits. Sections VI provides directions for future research.

II. Specification

Electricity is usually charged in blocks. In the PG&E experiment, the TOU and standard tariffs both consisted of inverted blocks. We adopt the approach developed by Burtless and Hausman (1978) and Hausman (1985) for nonlinear prices: the customer is considered to face a marginal price which is the rate in the block in which the customer consumes and to have "virtual income" which is the customer's income plus the difference between the marginal price and intra-marginal price for each lower block times the length of the block.[8] Let P_{pm} and P_{om} be the peak and off-peak marginal prices faced by the customer in month m and let VY_m be the virtual income of the customer in month m. Prices and virtual income vary over months because the customer's consumption level varies (putting the customer in different blocks) and the thresholds and rates under a given tariff are different in different seasons.[9]

For reasons to be described later, we assume a Gorman indirect utility function:

$$U_m = VY_m - \alpha_{pm}P_{pm} - \alpha_{om}P_{om} - \frac{1}{2}\beta_p P_{pm}^2 - \frac{1}{2}\beta_o P_{om}^2 - \theta P_{pm}P_{om}.$$

By Roy's identity, the peak and off-peak demand functions are:

$$X_{pm} = \alpha_{pm} + \beta_p P_{pm} + \theta P_{om}$$

$$X_{om} = \alpha_{om} + \beta_o P_{om} + \theta P_{pm}.$$

The parameters are specified to vary over time and customers as follows:

$$\alpha_{pm} = \bar{\alpha}_{pm} + \eta_1 + \mu_{pm}$$

$$\alpha_{om} = \bar{\alpha}_{om} + \eta_2 + \mu_{om}$$

$$\beta_p = \bar{\beta}_p + \eta_3$$

$$\beta_o = \bar{\beta}_o + \eta_4$$

$$\theta = \bar{\theta} + \eta_5$$

where $\bar{\alpha}_{pm}$ and $\bar{\alpha}_{om}$ are linear-in-parameters functions of observed variables where the variables may vary over m but the parameters do not. The vector $\tilde{\eta} = (\eta_1, \eta_2, \eta_3, \eta_4, \eta_5)$ varies over customers with distribution N(0,W) where W has elements denoted ω_{11}, ω_{12}, etc. The vector $\tilde{\mu}_m = (\mu_{pm}, \mu_{om})$ is independent of $\tilde{\eta}$ and uncorrelated over m.

To facilitate interpretation, consider the y-intercept of the peak demand function: α_{pm}. The average y-intercept for customers with the same observed variables is $\bar{\alpha}_{pm}$ in month m. Each customer's actual y-intercept differs from the average. This difference consists of a component η_1 that is constant over months, and a part μ_{pm} that varies over months and represents factors that reveal themselves to the customer on a month-to-month basis (such as whether the customer takes a trip). The customer knows η_1 and learns μ_{pm} when month m arrives; the researcher observes neither η_1, nor μ_{pm}. The other demand parameters are interpreted analogously.

The customer chooses TOU rates if its expected utility over the course of a year is greater under TOU than standard rates.[10] Let R_m and VY_m^S denote the marginal price and virtual income in month m that the customer would face under the standard tariff; and let P_{pm}, P_{om}, and VY_m^T be the marginal peak and off-peak prices and virtual income in month m under the TOU tariff. Total expected utility under each tariff is:[11]

$$TEU^T = \sum_{m=1}^{12} VY_m^T - \bar{\alpha}_{pm}P_{pm} - \bar{\alpha}_{om}P_{om} - \frac{1}{2}\bar{\beta}_p P_{pm}^2 - \frac{1}{2}\bar{\beta}_o P_{om}^2 - \theta P_{pm}P_{om}$$
$$-\eta_1 P_{pm} - \eta_2 P_{om} - \frac{1}{2}\eta_3 P_{pm}^2 - \frac{1}{2}\eta_4 P_{om}^2 - \eta_5 P_{pm}P_{om}$$

$$TEU^S = \sum_{m=1}^{12} VY_m^S - (\bar{\alpha}_{pm} + \bar{\alpha}_{om})R_m - \frac{1}{2}(\bar{\beta}_p + \bar{\beta}_o + 2\bar{\theta})R_m^2$$
$$-(\eta_1 + \eta_2)R_m - \frac{1}{2}(\eta_3 + \eta_4 + 2\eta_5)R_m^2$$

The customer calculates TEU^T and TEU^S exactly and chooses TOU rates only if $TEU^T > TEU^S$. The researcher, however, does not observe $\tilde{\eta}$ and hence ascribes a probability that the customer chooses the TOU tariff:

$$P^T = \text{Prob}(TEU^T > TEU^S)$$

$$= \text{Prob}\{[\sum_{m=1}^{12} VY_m^T - VY_m^S - \bar{\alpha}_{pm}(P_{pm} - R_m) - \bar{\alpha}_{om}(P_{om} - R_m) - \frac{1}{2}\bar{\beta}_p(P_{pm}^2 - R_m^2) - \frac{1}{2}\bar{\beta}_o(P_{om}^2 - R_m^2) - \bar{\theta}(P_{pm}P_{om} - R_m^2)$$

$$> [\sum_{m=1}^{12} \eta_1(P_{pm} - R_m) + \eta_2(P_{om} - R_m) + \frac{1}{2}\eta_3(P_{pm}^2 - R_m^2) + \frac{1}{2}\eta_4(P_{om}^2 - R_m^2) + \eta_5(P_{pm}P_{om} - R_m^2)]\}$$

The left hand side of the inequality is observed by the researcher; denote it as SYS. The right hand side, labeled -ERR, is not observed by the researcher but is known to be distributed normal with zero mean and variance $VAR = kWk'$ where the 1x5 vector k has elements $\Sigma(P_{pm}-R_m)$, $\Sigma(P_{om}-R_m)$, $\frac{1}{2}\sum(P_{pm}^2 - R_m^2)$, $\frac{1}{2}\sum(P_{om}^2 - R_m^2)$, $\sum(P_{pm}P_{om} - R_m^2)$ with the summations over m=1, ...

, 12 (such that $ERR=\tilde{\eta}k'$). Consequently, $P^T = \Phi(SYS/\sqrt{VAR})$, which is a probit model whose argument is nonlinear in parameters.

If the customer chooses TOU rates, its peak consumption in month m is:

$$X_{pm}^{T} = \bar{\alpha}_{pm} + \bar{\beta}_{p} P_{pm} + \bar{\theta} P_{om} + \eta_1 + \eta_3 P_{pm} + \eta_5 P_{om} + \mu_{pm} .$$

The customer knows all of these terms when month m arrives and calculates its demand exactly. The researcher, however, does not observe η_1, η_3, η_5, or μ_{pm}. Furthermore, while these terms have zero mean in the entire population, they do not have zero mean in the sub-population of customers who chose TOU rates. More fundamentally, the fact that the customer chose TOU rates reveals information to the researcher about the customer's actual parameters. Using Heckman's (1979) general result, we know that:

$$E(\eta_1 + \eta_3 P_{pm} + \eta_5 P_{om} + \mu_{pm} / TEU^{T} > TEU^{S})$$

$$= \frac{COV_{pm}^{T}}{\sqrt{VAR}} \; \frac{\phi(SYS/\sqrt{VAR}\,)}{\Phi(SYS/\sqrt{VAR}\,)} .$$

where COV_{pm}^{T} is the covariance of $\eta_1 + \eta_3 P_{pm} + \eta_5 P_{om} + \mu_{pm}$ with ERR in the probit model. This covariance is linear in parameters, with variables that are functions of prices and coefficients that are elements of W. For example, if W is diagonal (ie, no covariances), then:

$$COV_{pm}^{T} = -\omega_{11} \sum_{n=1}^{12} (P_{pn} - R_n) - \omega_{33} P_{pm} \frac{1}{2} \sum_{n=1}^{12} (P_{pn}^{2} - R_n^{2}) - \omega_{55} P_{om} \sum_{n=1}^{12} (P_{pn} P_{on} - R_n^{2}) .$$

The peak demand equation becomes:

$$X_{pm}^{T} = \bar{\alpha}_{pm} + \bar{\beta}_{p} P_{pm} + \bar{\theta} P_{om} + COV_{pm}^{T} \cdot K^{T} + \varepsilon_{pm}^{T} .$$

where $K^{T} = \frac{1}{\sqrt{VAR}} \; \frac{\phi(SYS/\sqrt{VAR}\,)}{\Phi(SYS/\sqrt{VAR}\,)}$

and $\varepsilon^T_{pm} \equiv \eta_1 + \eta_3 P_{pm} + \eta_5 P_{om} + \mu_{pm} - E(\eta_1 + \eta_3 P_{pm} + \eta_5 P_{om} + \mu_{pm} / TEU^T > TEU^S)$.

The remaining error term ε^T_{pm} now has zero mean by construction.[12]

The customer's off-peak demand, given that it chooses TOU rates, is:

$$X^T_{om} = \bar{\alpha}_{om} + \bar{\beta}_o P_{om} + \bar{\theta} P_{pm} + COV^T_{om} K^T + \varepsilon^T_{om}$$

where COV^T_{om} is the linear-in-parameters covariance of $\eta_2 + \eta_4 P_{om} + \eta_5 P_{pm}$ with ERR in the probit model. The demand equations for a customer that chose standard rates are:

$$X^S_{pm} = \bar{\alpha}_{pm} + \bar{\beta}_p R_m + \bar{\theta} R_m COV^S_{pm} K^S + \varepsilon^S_{pm}$$

$$X^S_{om} = \bar{\alpha}_{om} + \bar{\beta}_o R_m + \bar{\theta} R_m COV^S_{om} \cdot K^S + \varepsilon^S_{om}$$

where COV^S_{pm} is the covariance of $\eta_1 + (\eta_3 + \eta_5) R_m$ with ERR, COV^S_{om} is the covariance of $\eta_2 + (\eta_4 + \eta_5) R_m$ with ERR, and

$$K^S = \frac{1}{\sqrt{VAR}} \frac{\phi(SYS/\sqrt{VAR})}{\Phi(-SYS/\sqrt{VAR})}.$$

To aid interpretation, consider, for example, the case in which only ω_{11} is non-zero in W. That is, all customers have the same price coefficients and y-intercepts for off-peak demand and differ only in their y-intercepts for peak demand. The peak demand equation becomes:

$$X_{pm} = \begin{cases} \bar{\alpha}_{pm} + \bar{\beta}_p P_{pm} + \bar{\theta} P_{om} - \omega_{11} \sum_{n=1}^{12} (P_{pn} - R_n) K^T + \varepsilon_{pm}^T & \text{if customer chose TOU tariff} \\ \bar{\alpha}_{pm} + \bar{\beta}_p R_m + \bar{\theta} R_m + \omega_{11} \sum_{n=1}^{12} (P_{pn} - R_n) K^S + \varepsilon_{pm}^S & \text{if customer chose standard tariff.} \end{cases}$$

A customer who chose TOU rates consumes less in the peak than a customer who chose standard rates, for two reason. First, the peak price is higher under TOU rates than standard rates. The response to the higher price is captured by $\bar{\beta}_p$ which is presumably negative. Second, the customer chose TOU rates because its peak consumption was lower. This latter effect is captured in the last term before the error. K^T, K^S, $\Sigma(P_{pn}-R_n)$, and ω_{11} are necessarily positive, such that a positive amount is being subtracted in the function for the customer who chose TOU rates and a different positive amount added for a customer who chose standard rates. The ability of the model to differentiate these two directions of causation is one of its important features.[13]

Consider now the specification of the indirect utility function. The Gorman form gives linear demand equations with no income effect. There are three interrelated reasons for this specification. (1) We interpret the demand equations as applicable only within the range of price differences across tariffs, in which case linearity can be considered a first order approximation. (2) The model is intended primarily to provide information on the distribution of demand parameters for a population with given (fixed) characteristics, including income. As such the model is a short-run forecasting tool for use in designing tariffs for the population on which it is estimated. Households with greater income may consume more electricity and have different price responses than lower income families. These differences are captured, however, in these households' individual parameters, through higher α's and different β's. With the demand equations seen as applicable only within the relevant range of electricity prices, the inclusion of no income effect actually implies that the addition to virtual income that a tariff provides does not affect the customer's consumption. This assumption is not unreasonable, given the negligible size of this addition compared to total income. (3) The model places relatively few informational requirements on the customer. The parameters of linear demand correspond to information that the customer can intuitively consider, namely, the magnitude of demand in each period and the amount that the customer expects to respond to a unit change in price.

III. Data

In 1983, the California Public Utilities Commission ordered PG&E to test the customer acceptance, load impacts, and the cost and revenue implications of optional TOU tariffs. During 1984, PG&E developed an experimental design and recruited residential customers for participation in the experiment. In addition to a currently existing TOU tariff (labeled D-7), seven new TOU tariffs were established (labeled D-8A through D-8G).[14] The tariffs differed in the peak and off-peak prices that were charged in each block, the thresholds at which rates changed in each period (that is, the definition of the blocks), and the hours that were labeled as peak and off-peak. The characteristics of the tariffs are given in Table 1.

Residential customers whose consumption during the previous twelve months exceeded 800 kWh were targeted for recruitment. A random sample of this population was drawn in each geographical region, and sampled customers were offered one of the TOU tariffs. All customers who chose to switch to the TOU tariff were included in the experiment, as well as a random sample of customers who chose not to switch. Meters were installed on all customers in the experiment, beginning sometime around early 1985 (the date of meter installation varied over customers.) During 1985, all customers were billed under the standard, non-TOU rate (labeled D-1), though the TOU consumption of each customer was recorded. In early 1986, approximately half of the customers who had volunteered for the TOU tariff were switched to the TOU tariff that had been offered to them; the other half were continued on the standard rates. The selection of customers into these two groups was random. All customers' TOU consumption was recorded through the end of 1986.[15]

In short, the experimental design consists of approximately two years of TOU consumption data for each of three groups of customers: (A) customers who chose for the TOU tariff and were charged under standard rates in 1985 and under TOU rates in 1986, (B) customers who chose for the TOU tariff but were charged under the standard tariff for the entire two-year period, and (C) customers who chose the standard tariff and were charged standard rates for both years. The design allows comparison of: (1) pre- versus post-treatment consumption of customers who chose TOU rates (group A in 1985 compared to 1986), (2) pre-treatment consumption of customers who chose TOU tariffs versus that of customers who chose standard rates (1985 for groups A and B compared to group C), (3) consumption of customers who chose TOU rates versus that of customers who chose standard rates (1986 for group A compared to group C), and (4) consumption of customers who chose TOU rates and were placed on TOU rates versus consumption of customers who chose TOU rates but were placed on standard rates (1986 for group A compared to group B.) Details of the experiment are provided in PG&E (1985).

Table 2 gives the total number of eligible customers and the number included in the analysis. For the estimated demand curves to be meaningful, the same definition of the peak period is required for all customers (or, alternatively, the demand parameters must be explicitly represented as functions of the definition of the peak, an approach which we did not attempt.) Schedules D-7, D-8C, D, E, and G impose the same definition of the peak, while the other schedules use different definitions. We eliminated from analysis all customers who were offered schedules D-8A, B, and F,[16] leaving the number of customers given in the next-to-last row of Table 2. In all the empirical analysis, customers were weighted by the inverse of their sampling proportion, given in the last row of the table.

IV. Estimation

For estimation, we specify an objective function whose contribution for each customer is:

$$\delta \log P^{T} + (1-\delta) \log (1-P^{T}) - \left[\sum_{m=1}^{M} (\varepsilon_{pm}/2\sigma_p)^2 + (\varepsilon_{om}/2\sigma_o)^2 + \log \sigma_p + \log \sigma_o + \log (2\pi) \right]$$

where $\delta = 1$ if the customer chose TOU rates, and zero if the customer chose standard rates,

P^T is the customer's probability of choosing TOU rates,

M is the number of months for which there are observations on peak and off-peak consumption,

ε_{pm} is the difference between actual and predicted peak consumption in month m (where the predictor is conditional on tariff choice),

ε_{om} is defined analogously for off-peak consumption, and

σ_p, σ_o are the standard deviations of ε_{pm} and ε_{om}, respectively.

The parameters that maximize this function are consistent method-of-moments (MOM) estimators at exogenous marginal prices and virtual income (Amemiya, 1983). As motivation, note that when the standard deviations σ_p and σ_o are treated as their true functions of the parameters and variables, then the objective function becomes the log-likelihood function and the MOM estimator becomes MLE. When treated as constant parameters, the MOM estimator is less efficient than MLE but, given the highly nonlinear form of the standard deviations, is more manageable numerically. We estimate with the standard deviations treated as parameters.[17]

Under block-rate tariffs, marginal prices and virtual income depend on consumption and hence are endogenous. Like Hausman and Trimble, we adopt an approach similar to that proposed by Rosen (1976) and Hausman, Kinnucan, and McFadden (1979), namely to use estimated marginal prices and virtual incomes that depend only on exogenous factors. In particular, a regression model of TOU consumption is estimated that includes exogenous variables only. This model is used to predict each month's TOU consumption for each customer. Under each tariff (the standard tariff and the TOU tariff that the customer was offered), the block in which this predicted consumption falls is identified. The marginal price and virtual income associated with this block is used as the estimate for price and virtual income for that customer in that month under that tariff. For the purpose of calculating these marginal prices and virtual income, we used the regressions of TOU consumption that were performed by Goett on these data and reported in his Appendix B. Note that, given the nonlinearity of the model, using estimated marginal prices and virtual income is inconsistent; however, we believe the inconsistency is small.[18]

The data set consists of over 60,000 monthly observations, which exceeds the capacity of both our hardware and software. For estimation, we drew a random one-third subset of the monthly observations. Sequential estimation results were taken as starting values. Iteration toward the maximum was initiated using the BHHH approximation to the Hessian since this approximation provides relatively quick movement (Berndt, et al., 1974). Once "convergence" was achieved under this approximation, iteration was continued by the Davidon-Fletcher-Powell procedure, which provides a more accurate (though slower) calculation of the Hessian, particularly near the maximum of the objective function (Fletcher and Powell, 1963). The resulting values are given in column 1 of Table 3. To verify the results, a second one-in-three sample was taken and subjected to the same estimation procedure. The results, given in column 2, are very close to those obtained on the first sample. We utilize the estimates in column 1 for all the following discussion and calculations.

The estimated parameters suggest the following. (i) "Cooling degree days" is a variable that reflects average temperatures during the month and indicates the extent to which an air conditioner is needed, or will be used, during the month.[19] It enters only for households with air conditioners. The positive coefficient indicates that households with an air conditioner have a higher level of electricity use (a higher y-intercept) than other households, both in the peak and the off-peak. Furthermore, the level of the household's consumption is higher in hot months (when cooling degree days is high) than in cooler months. (ii) Households with more members and larger houses have higher consumption (y-intercept) in the peak and off-peak. (iii) The magnitude of these impacts is greater in the off-peak than the peak, reflecting the fact that the off-peak period is considerably longer than the peak (18 hours vs. 6 hours) and average consumption in the off-peak is greater than that in the peak (893 kwh/month vs. 184 kwh/month.) (iv) The average same-price coefficients ($\bar{\beta}_p$ and $\bar{\beta}_o$) are negative as expected. These estimated coefficients imply average price elasticities of -0.15 in the peak and -0.25 in the off-peak. These elasticities represent short-run response, with the household's appliance holdings and housing characteristics held constant. They are averages over all customers; the model implies that, for customers with the same y-intercepts, those with higher elasticities are more likely to choose TOU rates. Goett estimated average elasticities of -0.16 and -0.35 in the peak and off-peak. His estimates are slightly higher than ours. However, his specification does not reflect the bi-directionality of causation (by which customers choose a tariff based on their demand and then, given their tariff, respond to the marginal prices under the tariff.) Consequently, Goett's estimates can be expected to capture some of the effect of demand on tariff choice rather than simply the effect of prices on demand.[20] (v) The cross-price coefficient ($\bar{\theta}$) implies that peak and off-peak consumption are substitutes. This result is consistent with the findings of Caves et al and Hausman and Trimble. (Goett does not enter a cross-price term.) (vi) The standard errors of the same-price coefficient in the peak and the cross-price coefficient are large (about the same size as the coefficients themselves), implying considerable uncertainty. The elasticities reported here should therefore be taken as highly provisional until more precise estimates can be obtained in future research.[21]

We were not successful at estimating covariance terms, and, as stated above, the estimated means and variances of the price terms have large standard errors. The problem, of course, is high correlations among the variables that enter the analysis. This multicollinearity is partially a result of the specification and partially of the data. The variables that enter COV are various functions of prices and hence have a tendency to be highly correlated. This aspect of the specification is unavoidable given that the customer's tariff choice is related to its demand parameters. This inherent difficulty of the model is compounded, however, by the design of PG&E's experiment. The optional TOU tariffs in PG&E's experiment were designed such that, for each tariff, the "average price" in the peak is 2.5 times that in the off-peak, where average price in each period is defined as the total revenues that PG&E would obtain for consumption in that period if all customers were charged under the TOU tariff, divided by the total kWh's that would be consumed in the period (with this latter figure calculated on the basis of some assumptions about the TOU consumption of customers; for details, see PG&E, 1985.) Marginal prices in the peak and off-peak are not perfectly correlated under the TOU tariffs because of the block rate nature of the tariffs: different customers consume in different blocks such that the ratio of marginal prices for each customer is not 2.5. However, the amount of independent variation in peak and off-peak prices is severely limitied by this aspect of the experimental design.

V. Impacts of PG&E's Optional TOU Rates

The estimated model is used to determine the impacts of the optional TOU rates that PG&E offered under its TOU experiment. Table 4 contains the results. Recall that PG&E designed several TOU rate schedules and offered each schedule to a different group of customers. We restricted out analysis to the five schedules that used the same definition for the peak period, namely, noon to 6 p.m. on weekdays. Each column in Table 4 gives results for the customers who were offered each rate schedule. For example, the first column indicates that 11.3% of the customers who were offered TOU schedule D7 chose to be on the schedule. Of those customers who chose this TOU schedule, the model predicts that their consumption in the peak would be 184.9 kWh per month, on average, if they faced the standard rates. (Note that this is the amount that they are predicted to consume under standard rates even though they faced TOU rates.) Average peak period consumption is 192.4 kWh/month for customers who chose not to switch from standard rates to the D7 TOU rates.[22] Other figures in the table are interpreted analogously.

The estimated consumption levels and elasticities given in parts I and II of the table are used to compare customers who chose TOU rates with those who chose standard rates. For all five optional TOU rate schedules, the model indicates that customers who chose TOU rates would have lower peak consumption than customers who chose standard rates, if both groups of customers faced standard rates. This result is expected since customers with a lower ratio of peak to off-peak consumption under standard rates obtain a greater bill reduction by switching to TOU rates. Customers who chose TOU rates are found to have, on average, more elastic demand in the peak and less elastic demand in the off-peak. This result is consistent with the findings of Goett. The higher peak elasticity is intuitive: customers who are more able and willing to reduce consumption in the peak are more likely to choose TOU rates. The lower off-peak elasticity is theoretically possible but not as intuitive. With all other factors (such as consumption levels) held constant, customers who are <u>more</u> price responsive are expected to choose TOU rates more readily since they can benefit more from the lower off-peak price. However, all other factors are not held constant in the population of all customers; in particular, the level of off-peak consumption is higher for customers who chose TOU rates than those who chose standard rates. With larger off-peak consumption, the average off-peak elasticity can be smaller for customers who chose TOU rates compared to those who chose standard rates, even though, if consumption levels were the same, their average elasticity would be greater.

Part III of the table gives estimates of the impact of the TOU rates on the customers who chose them, as well as the resulting impacts on the utility. As expected, customers who chose TOU rates are forecast to decrease their consumption in the peak and increase their consumption in the off-peak in response to TOU prices. These estimated changes are the price response only, after netting out the differences in demand that cause the customers to choose TOU rates. This latter quantity is the difference in estimated consumption under standard rates, which is given in Part I of the table. For schedule D7, this quantity in the peak is 184.9 - 192.4 = -7.5. Comparing this figure with the price response of -18.84 indicates that, for this schedule, 72% of the observed difference in peak consumption between customers who chose TOU rates and those who chose standard rates is due to price response; the other 28% is the difference in demand that induced the customers to choose TOU or standard rates. Using the now-common terminology, the "price effect" is two-and-a-half times larger than the "selection effect" (i.e., 72/28) for tariffs D7. The price effect is estimated to exceed the selection effect for all the tariffs except D-8G.

This result is consistent with Caves et al., the only other study to provide information that can be used to infer the relative magnitudes of the price and selection effects. In particular, Caves et al. estimated that peak consumption under non-TOU rates would have been 19% of total consumption for customers who chose TOU rates, while the average share for all customers was 20%. They conclude that "these data show no indication that the initial volunteers are customers that can take better advantage of the TOU rates than the rest of the population without shifting usage" (p. 96). They also estimated that customers who chose TOU rates reduced their peak consumption to 14.3 precent of total consumption due to the TOU prices. These figures imply that the price effect constitutes about 80% of the difference in peak consumption between customers who chose TOU rates and those who did not, with the selection effect constituting the other 20%.[23]

Under all five TOU schedules, customers are found to increase their off-peak consumption more, in absolute terms, than they decrease their peak consumption. However, since off-peak consumption levels are greater than peak consumption levels, peak consumption decreases by a greater percentage than off-peak consumption increases. Under four of the five TOU rate schedules, customers who chose TOU rates receive smaller bills, on average, under TOU rates than they would have received under standard rates. For the other schedule (i.e., D-8D), customers' average bills increase under TOU rates. The reason for this increase is discussed below, after the discussion of utility costs and profits.

The change in utility costs is calculated by multiplying the change in peak and off-peak consumption by the marginal cost of production in each period. The California Public Utilities Commission has approved TOU marginal cost figures for PG&E.[24] The relevant figures are 0.09963 and 0.03846 dollars per kWh in the peak and off-peak, respectively, for summer months, and 0.04207 and 0.03121 for peak and off-peak in the winter. Using these figures, the utility's costs are calculated to have risen as a result of the optional TOU rates. That is, the extra cost associated with the additional off-peak consumption is greater than the cost savings from the reduction in peak consumption.

The change in profits is the change in the customer's bill (which is utility revenue) minus the change in costs. Note, of course, that this change in profit is not actually retained or borne by the utility, but is (at least partially) passed onto consumers. For all five TOU schedules, the utility's profits are predicted to have declined, which means that, under a regulatory constraint of constant profits, the optional TOU rates contributed to a general rate increase.

The only schedule to increase PG&E's profits, and hence Pareto dominate the offering of standard rates alone, is D-8D. This schedule differs from the others in an important way: it has no tiers. All peak consumption is charged at the same price, as is all off-peak consumption. Essentially, by removing the lower prices in the first tier, D-8D is raising the price that customers pay (relative to the standard rates) for consumption in the first tier. Recall that the issue of whether the utility gains from the offering of an optional TOU tariff depends on which of two factors dominates: (1) customers whose bill for their given consumption will drop by switching to TOU rates will choose TOU rates; this action decreases utility revenues without changing its costs; versus (2) customers who choose TOU rates will adjust their consumption in response to the rates; this behavior increases utility profits. By eliminating the first-tier discount, D-8D reduces the magnitude of the first factor, thereby allowing the second factor a greater chance to dominate.

Note that the only tariff to Pareto dominate is also the only tariff under which customers who choose the tariff incur a larger energy bill than under standard rates. This increased revenue to the utility is what allows the utility to increase profits under D-8D and not under the other TOU tariffs, since its costs increase under each tariff. Goett, the only other analyst to report bill impacts for optional TOU electricity rates, obtained the same result, namely, that customers who chose the TOU rates received a larger bill than they would have under standard rates. In Goett's analysis, as in ours, the consumer necessarily chooses the tariff that provides the greater surplus (i.e., it is not possible for the customer to have chosen the "wrong" tariff.) Therefore, an increased bill implies that the off-peak price effect (i.e., the increase in consumption in response to the lower off-peak price) dominates the selection and the on-peak price effect.[25]

For the other tariffs, PG&E loses profits. There are two reasons. First, customers' price responses are not sufficiently large to overcome the bill reduction that customers who choose TOU rates receive for the consumption that they would have had under standard rates. However, a second issue may be more important in this particular setting. Note that the marginal cost of producing energy in the peak period was, at the time of these tariff offerings, lower than the third tier price under the standard rates (peak-period marginal cost was 0.09963 $/kWh in the summer and 0.04207 in the winter, while the third tier price under standard rates was 0.113.) Consequently, a reduction in peak consumption in response to the TOU rates decreases utility profits and total surplus.

The proofs that optional TOU tariffs can be designed that increase total surplus and even Pareto dominate compared to standard rates alone are predicated on the assumption that marginal price under standard rates exceeds marginal cost in the off-peak and is below marginal cost in the peak (MacKie-Mason, 1990; Train, 1988). Under PG&E's conditions in 1986, this relation did not hold. It is interesting in this regard, therefore, that an optional TOU schedule was found that does Pareto dominate (namely, D-8D.) This finding is a reminder that the proofs provide conditions for the existence of surplus-enhancing optional tariffs but do not imply that such tariffs do not exist if the conditions are not met.

Even though most of the experimental rates do not provide Pareto dominance, they may increase total surplus. The last two rows of Table 4 provide estimates of the change in consumer surplus and total surplus under each of the tariffs. The customers who chose the optional TOU rates are estimated to have obtained greater surplus in the amount of $1.81 to $9.96 per month, depending on the tariff. With the average bill for these customers being about $84, the gain in consumer surplus is about 2-12% of the customers' bills. Hausman and Trimble, the only other analysts to report such figures, found that the optional TOU rates in Vermont increased consumer surplus by $6 per month in 1980 dollars, which comes to $9.16 in 1985 dollars. The gain in Vermont is larger than that under most of PG&E's rates perhaps because: (i) energy consumption and energy bills are generally larger in Vermont than northern California (though the average is not reported by Hausman and Trimble to confirm this relation for their sample), and (ii) the Vermont TOU rates were permanent, such that a larger impact could be expected than for PG&E's experimental rates.

Adding the gain in consumer surplus with the change in utility profits gives the change in total surplus. The optional TOU rates are estimated to have increased total surplus by $1.41-$2.55 per month for each customer who chose the TOU rates. Tariff D-8D clearly provides the greatest surplus gain: the largest share of customers choose this rate (14.55% of all customers who were offered it) and the gain in total surplus per customer who chooses it is largest ($2.55/month). As discussed above, this rate is also the only one to provide Pareto dominance.

For the four other tariffs, total surplus increases, but without Pareto dominance. In these cases, the regulator must decide whether the surplus gain is worth the ethical and political difficulty of introducing a non-Pareto-dominating change. Hopefully, by providing estimates of the magnitude of the surplus gain and the loss of utility profit, regulators will be in a better position to make this choice.

The analysis up to this point has ignored measurement costs, i.e., the cost of installing TOU meters for customers who choose TOU rates. The reason is largely pragmatic, and somewhat conceptual. There is considerable controversy about the appropriate measurement cost to apply. Current costs do not necessarily represent the relevant costs for two reasons. First, over time, technology improvements have reduced these costs considerably. Evaluating experimental TOU rates on the basis of past or current measurement costs might not provide the best indication of whether the tariffs should be continued into the future. Second, returns to scale are considered to be substantial, such that the average cost for the few meters that are installed under experimental rates are not indicative of the cost for general (i.e., large-scale) offerings of optional TOU rates.

The figures in Table 4 provide an upper limit to measurement costs under which the experimental tariffs are surplus enhancing. For example, if incremental cost of a TOU meter is less than $1.41 per month, then all of the optional tariffs increase total surplus including measurement costs. If the cost exceeds $2.55 per month, then none does.

PG&E (1993) reports that the incremental cost of TOU meters over standard meters is $2.90 per month per meter -- which comes to $2.17 in 1985 dollars. This amount exceeds the gain in total surplus for four of the five experimental tariffs, the exception being D-8D. Therefore, with measurement costs included and using the PG&E estimate of measurement costs, only one of the five tariffs provides an increase in total surplus. Furthermore, when these measurement costs are included in the calculation of utility profits, profits decline under all the tariffs including D-8D, such that none of the tariffs provides Pareto dominance. These results emphasize the importance of measurement costs in determining the welfare impacts of TOU rates.

VI. Further Work

Perhaps the most interesting area of investigation is to use the model to calculate the optimal optional TOU rates, that is, the rates that provide the greatest increase in total surplus (alternatively with and without a break-even constraint for the utility). Consumer surplus and utility profits under standard rates, mandatory TOU rates, and the optimal optional TOU rates can be compared. In fact, the optimal Pareto dominating optional TOU rates can be identified, such that the loss of surplus that results from maintaining Pareto dominance can be measured. These welfare calculations will provide information for regulators in determining whether to pursue TOU rates and, if so, in what form.

Other avenues for future research involve the specification and estimation of the model. Estimation methods are required that allow estimation of the entire model simultaneously.

Simulation procedures for estimation are a promising possibility. The specification can be generalized in several ways to represent more accurately customers' choice process. The most prominent potential generalizations involve: (i) adding income effects, (ii) allowing more flexible cross-price effects, (iii) allowing additional factors (representing, for example, risk, transaction costs, or altruistic concern about the environment) to enter the behavior and surplus of customers, and (iv) capturing the learning process of customers, by which customers learn about their TOU demand and price responses by being under a TOU tariff. These generalizations will add to the complexity of the estimation and hence will need to be undertaken in conjunction with the development of improved estimation methods.

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1. If the standard rate is sufficiently high that all customers choose the TOU rates, then the situation is equivalent to mandatory TOU rates. Optional TOU rates are only meaningfully defined as occurring in situations in which some customers choose the standard rates.

2. It is conceivable that, when measurement costs are considered, that welfare could be greater under optional TOU rates than mandatory ones. This outcome will occur if the customers whose deadweight loss under optional TOU rates is less than the TOU measurement costs happen to be the customers who decide to remain on standard rates. It is unlikely, however, that tariffs could be designed that obtain this outcome; the issue has not been explored in the literature.

3. The issue of Pareto dominance hinges on the provider's profits even if the provider is required, through regulation, to earn zero profit. If the provider's profits decrease with the offering of optional TOU rates, then all rates, including standard rates, will be raised to allow the provider to recoup the loss; this rate increase necessarily hurts the customers who choose to remain on standard rates. Conversely, if the provider's profits increase, then the standard rates can be decreased, such that all customers benefit and the provider remains at zero profit.

4. Or, more precisely, a reduction in opposition. Parties often oppose the distribution of gains even though all parties gain.

5. There is a critical distinction that affects the interpretation and use of the models. The telecommunications models allow each customer's choice to depend on a random term that does not relate to demand, representing an intrinsic preference among tariffs. The addition of this term allows for a better fit but changes the welfare analysis of optional tariffs considerably. When the extra term is included, the measure of consumer welfare consists of the traditional consumer surplus--i.e., the area under the known demand curve--plus other factors that this extra term represents; as one would expect when the measure of welfare changes, the conditions for optimality also change. For example, with this term, optional tariffs with prices not at marginal cost can provide greater total surplus than marginal cost pricing (Train, forthcoming). Stated succinctly: it is not possible to conduct <u>traditional</u> welfare analysis on a model that includes such a term. Since we wish to calculate changes in traditional consumer surplus under the optional TOU rates, our model does not include this term. However, as a result, the estimated distribution of demand parameters is required to allow each customer's chosen tariff to provide the greatest surplus for that customer. This modeling strategy has implications that are discussed later in the paper.

6. Hausman and Trimble analyzed data from Vermont's optional TOU rates, which were permanent rather than experimental. The non-experimental nature of the rates meant that prices under the TOU tariff did not vary over customers and that TOU consumption was recorded only for customers who chose the TOU rates. These limitations hinder the econometrics. However, the permanence of the rates can be expected to induce long-run responses by customers which might not be captured in experiments of limited duration.

For example, customers can invest in timers for air-conditioners and other appliances which are cost-effective for the customer only if the TOU rates were expected to continue for a sufficiently long period.

7. The same problem plagued previous work. Cox was only able to estimate a restricted version of his model which eliminated nearly all forms of customer heterogeneity. Hobson and Spady reduced the number of parameters to be estimated by aggregating usage by TOU and distance into one aggregate measure, thereby eliminating the ability of the model to examine TOU demands.

8. For example, if the tariff is 7¢ per kwh for up to 500 kwh's and 10¢ beyond and the customer consumes in the second block, then the marginal price is 10¢ and virtual income is the customer's income plus $15 (3¢/kwh times 500 kwh's), which is the "discount" the customer receives from the lower first block price.

9. Estimation is complicated by the endogeneity of marginal prices and virtual income. Our method of handling this endogeneity is described in section IV; it consists of calculating marginal prices and virtual income at predicted levels of consumption, with the predictions being based on exogenous variables only.

10. Under PG&E's experiment, the TOU rates lasted one year and customers could not switch to TOU rates after initially choosing standard rates. Customers were allowed to drop out of the experiment, in which case a customer on TOU rates would return to standard rates. In fact, however, most of the customers who dropped out did so because they moved. In non-experimental applications, customers can switch between rates; however, due to psychic and actual transaction costs, customers can be expected to use some horizon

longer than a month for evaluating tariffs.

11. (i) The customer does not observe $\tilde{\mu}_m$ prior to month m and utilizes its expectation, which is zero. (ii) The customer would utilize expected, or "normal", weather in the calculation of weather variables that enter as components of $\bar{\alpha}_{pm}$ and $\bar{\alpha}_{bm}$. For the PG&E data, estimated parameters are essentially the same whether actual or normal weather is used. (iii) The customer might apply a time discount. However, in the PG&E experiment, the customer did not know when the TOU rates would start and hence could not determine when to start the discounting. In any case, discounting month by month over one year would not materially affect the results.

12. Note that the customer reveals information about its $\tilde{\eta}$ when choosing a tariff, but not about $\tilde{\mu}_m$. At the time of choosing between tariffs, the customer is assumed not to know $\tilde{\mu}_m$, which is revealed to the customer only when month m arrives. COV_m depends therefore on elements of W but not on the distribution of $\tilde{\mu}_m$. The remaining error term ε_{pm}^T incorporates μ_{pm} entirely plus the researcher's remaining uncertainty about η_1, η_3, and η_5.

13. When elements of W relating to price parameters (e.g., ω_{22}) are non-zero, the two directions of causation are not neatly separated. In particular, the terms in COV·K include the expected extra price response (over the average response $\bar{\beta}$) of customers who chose TOU rates. The two directions of causation can nevertheless still be separated; the results of such separation for PG&E's experimental TOU rates are given in Section V.

14. Even though D-7 had been offered previously, it was essentially a new tariff at the time of the experiment. Prior to 1984, D-7 had been offered to a very limited number of

customers. In 1984, D-7 was substantially modified to follow the same principles of TOU tariff design that were used for the D-8 tariffs (mainly, that they be revenue neutral for an average customer). When recruitment for the D-8s was initiated, customers on D-7 were notified of the change in D-7 and could switch to standard rates. Note, however, that this recruitment process creates potential for self-selection bias: customers who had chosen the original D-7 were included in the experiment while those who were offered but rejected the original D-7 were included in the experiment only if they happened to be selected for recruitment for one of the D-8 tariffs. Given the limited nature of the original D-7, it seems that the bias would be small.

15. Customers who chose a TOU tariff were allowed to switch back to the standard tariff during the course of the experiment, but customers who initially chose the standard tariff were not allowed to later switch to a TOU tariff. In actuality, few customers "dropped off" of the TOU tariffs (perhaps because only half of the customers who chose TOU tariffs were ever put on the TOU rates, and the other half were only on TOU rates for the second of the two years). Customers who dropped off the TOU rates usually did so because they moved. All customers who dropped off the TOU rates were eliminated from the analysis.

Ideally, the model would be specified to represent repeated choices over time. The customer initially chooses between TOU and standard tariffs knowing that it is possible to later drop off the TOU tariff but it is not possible to later switch from standard to TOU rates. The customer therefore perceives an option value to choosing a TOU tariff. At each subsequent point in time, a customer who initially chose a TOU tariff faces a choice of whether to drop off the tariff, knowing that switching to the standard tariff is irreversible. A model of this type is extremely difficult to estimate, particularly when serially correlated errors are incorporated. However, it is a very interesting, and probably fruitful, direction for econometric analysis.

16. Note that, to avoid self-selection bias (Heckman, 1979), all customers who were offered these schedules were eliminated, not just customers who chose these schedules. We re-estimated the models using all households, including those who were offered schedules D-8A, B, and F. The goodness-of-fit statistics became worse, the standard errors for most parameters became larger, and some estimated parameters took the wrong signs.

17. Treating these standard deviations as constants does not mean that unobserved customer heterogeneity is ignored in estimation. In particular, the variances in the demand parameters (i.e., the elements of W) enter in the predicted values of peak and off-peak consumption conditional on tariff choice (i.e., enter COV and K in the prediction of X) and are estimated as part of the model. These estimated variances in the demand parameters provide the "best" fit between predicted and actual consumption for the entire sample of customers. The σ_p and σ_o are the standard deviations of the fitting errors, that is, of the difference between the predicted and actual consumption. Treating these standard deviations as constants means that the extra information about the means and variances of demand parameters that is contained in the heteroscedasticity of these fitting errors is not used in estimation.

18. If the marginal price in each period depended on consumption in that period only, consistency would be attained through the estimation procedure of Burtless and Hausman

(1978), albeit at great computational cost. However, under some of the optional TOU rates, marginal price in each period depends on combined consumption in both periods, and the Burtless/Hausman procedure does not generalize to this situation.

19. Cooling degree days is defined as the sum over all days in the month of: max(T-65,0), where T is the average temperature of the day. That is, for each day, cooling degrees is the extent to which the average temperature exceeds 65 degrees; the daily cooling degrees are summed over all days in the month to obtain the monthly cooling degree days.

20. Elasticity estimates are not available for other studies of optional TOU rates. Caves et al estimate a model of the share of consumption in the peak and off-peak given total consumption in both periods; elasticities can therefore not be determined. Hausman and Trimble report that their estimated parameters imply that nearly all of a household's energy expenditures are "committed," which implies that price elasticities are very low. However, they do not report elasticity estimates.

21. Even though these estimated elasticities conform to previous findings, the previous estimates also had large standard errors.

22. The figures in Table 4 utilize each customer's observed consumption as much as possible, so as to minimize prediction errors. In particular, for consumption under the tariff that the customer actually chose (i.e., was actually charged under), the customer's actual consumption was used. For example, for customers who chose standard rates, average consumption under standard rates is the average of the actual consumption for these customers. Predicted consumption under a tariff that the customer did not choose (i.e., was not actually charged under) was calculated by taking the customer's actual consumption under the tariff that the customers was actually charged under and

adding/subtracting an amount that represents the estimated price effect for that customer.

23. Goett provides indirect evidence that his model also implies that the price effect exceeds the selection effect. In particular, he estimated that revenues from customers who chose TOU rates are higher under the TOU rates than they would have been under standard rates. Since the selection effect necessarily decreases revenues (i.e., the customer chooses the TOU rates because its bill decreases for its consumption under non-TOU rates), this result implies that the selection effect must be comparatively small. Or, more precisely, the price effect in the off-peak (i.e., the increase in off-peak consumption in response to the lower off-peak price) is sufficiently large to dominate both the selection effect and the price effect in the peak.

Opposite results have been obtained for optional telecommunications tariffs. In their analyses of flat-rate and optional measured tariffs for local service, Hobson and Spady (1988) and MacKie and Lawson (1993) found the selection effect to be far larger than the price effect. There is no immediately obvious reason for this difference in customer behavior with respect to optional TOU electricity rates and local telecommunications rates. The telecommunications studies differ methodologically from the current study in two ways that could possibly explain the difference: (i) they include more demographic variables, thereby allowing for more observed heterogeneity, and (ii) they include a constant for the "bias" toward flat-rtate service -- a variable omitted from the current study for the reasons given in footnote 5. However, Caves et al. and Goett are similar to the telecommunications studies in these regards and yet also find that the selection effect is relatively small.

24. These costs consist of variable cost of production given capacity plus marginal capacity cost as reported in PG&E (1991).

25. This result, while theoretically possible, might actually be an artifact of the constraint that the customer's chosen tariff provides the greater surplus. In particular, the estimated demand parameters are those that best explain the customer's tariff choice and observed consumption levels. Since the chosen tariff is required to be the one with the greater surplus, the demand parameters are required to provide sufficient price response for the actual tariff choices to seem "rational." If indeed the chosen tariff does not provide the greater surplus (i.e., customers make mistakes in their choice of tariff), then the estimated price responses would probably (though not necessarily) be too large.

An alternative approach is to enter variables in the tariff choice specification that do not enter the demand equations (such as a dummy capturing the preference of one tariff over another independent of the surplus obtained under each tariff.) This approach results in a better fit but eliminates the analyst's ability to conduct welfare analysis with the model (as discussed in footnote 5 and Train, forthcoming). To allow for meaningful welfare analysis, variables that enter tariff choice but not the demand equations were not included in the analysis. However, a possible result of this restriction is that the estimated price effect might be unduly large so as to "explain" customers' tariff choices.

The solution, of course, is to generalize the behavioral theory of tariff choice to account for dynamic factors, such as risk and transaction costs, that affect ex ante tariff choice but do not enter the ex post demand equations, and then to derive welfare results under this generalized behavior. Empirical models that are consistent with this generalized behavior could then be estimated, with the surplus calculations from these empirical models necessarily consistent with the theoretical welfare results. This is clearly the direction for future research on tariff choice.

Table 1

TARIFF CHARACTERISTICS
January 1, 1985

Standard Tariff	Price per kWh		
	Tier 1	Tier 2	Tier 3
D-1	.06688	.08694	.11300

TOU Tariffs	Price per kWh				Peak Time
	Peak		Off-peak		
	Tier 1	Tier 2	Tier 1	Tier 2	
D-7	.12862	.19228	.05145	.07691	noon - 6:00 p.m. M-F
D-8A	.12862	.19228	.05145	.07691	summer: noon - 6:00 p.m. M-F winter: 3:00 - 6:00 p.m. M-F
D-8B	.12862	.19228	.05145	.07691	2:00 - 8:00 p.m. M-F
D-8C	.15917*	.19228	.04380*	.07691	noon - 6:00 p.m. M-F
D-8D	.17037	---	.06815	---	noon - 6:00 p.m. M-F
D-8E	.11147	.16664	.05573	.08332	noon - 6:00 p.m. M-F
D-8F Summer	.13492	.19464	.05815	.08390	noon - 6:00 p.m. M-F
D-8F Winter	.08216	.11853	.05477	.07902	3:00 - 9:00 p.m. M-F
D-8G	.12540	.16301/.19604**	.05225	.06792/.08168**	noon - 6:00 p.m. M-F

Tier lengths depend on the customer's location and whether or not the customer is "all electric." Different tier lengths apply in summer and winter.

*Peak and off-peak consumption are combined to determine whether the Tier 1 price is charged (i.e., the Tier 1 threshold is based on total kWh in peak and off-peak).

**D-8G contains three tiers in each period.

Table 2

CUSTOMER SAMPLE

	Total	Customers who chose:	
		TOU Tariff*	Standard Tariff**
Mailings	36,742	4,081	32,661
Customers offered D-7, D-8C, D, E, G	31,727	3,532	28,195
Customers included in analysis	2,571	2,343	228
Weight		0.122	10.021

Weight equals the proportion of the population that chose each tariff divided by the sample proportion. For customers who chose the TOU tariff, 0.122 = (3,532/31,727) / (2,343/2,571). Weight is therefore proportional to the inverse of the sampling frequency among customers who chose each tariff.

*These customers consist of those placed on TOU rates in 1986 and those who were required to remain on standard rates in 1986. That is, these customers consist of groups A and B as described in the text.

**These customers consist of group C as described in the text.

Table 3

ESTIMATED MODEL OF TOU DEMAND

Variable	Parameter	Estimate (standard errors in parentheses)	
		random sample 1	random sample 2
Components of y-intercept of peak demand	$\bar{\alpha}_{pm}$		
Constant		161.7 (38.3)	164.1 (89.68)
Cooling degree days if household has air conditioner, zero otherwise		27.59 (1.16)	35.75 (2.43)
Number of members in household		49.39 (1.70)	51.6 (6.02)
February dummy		-14.23 (30.04)	-14.78 (61.35)
March dummy		-35.62 (27.4)	-36.31 (62.0)
April dummy		-44.77 (23.88)	-46.08 (56.3)
May dummy		-43.99 (25.39)	-44.1 (55.27)
June dummy		-30.15 (27.13)	-30.51 (52.53)
July dummy		-14.52 (26.04)	-14.28 (53.03)
August dummy		-27.58 (25.47)	-28.11 (50.67)
September dummy		-41.8 (25.75)	-42.78 (50.91)
October dummy		-43.0 (25.46)	-43.73 (51.33)
November dummy		-11.32 (27.47)	-12.55 (61.4)
December dummy		7.39 (29.93)	6.97 (61.91)

Table 3, continued Variable	Parameter	Estimate (standard errors in parentheses)	
		1	2
Components of y-intercept of off-peak demand	$\bar{\alpha}_{om}$		
Constant		951.14 (2.60)	954.33 (7.43)
Cooling degree days if household has air conditioner, zero otherwise		73.19 (0.43)	73.48 (0.82)
Number of members in household		48.96 (0.24)	48.56 (0.75)
February dummy		-135.71 (1.27)	-135.13 (3.84)
March dummy		-172.58 (1.26)	-172.04 (4.38)
April dummy		-251.1 (1.23)	-248.2 (3.49)
May dummy		-270.72 (1.33)	-267.99 (4.06)
June dummy		-275.13 (1.71)	-272.62 (4.08)
July dummy		-267.55 (1.52)	-264.7 (3.69)
August dummy		-283.26 (1.41)	-280.97 (3.77)
September dummy		-297.8 (1.45)	-294.69 (3.52)
October dummy		-261.45 (1.65)	-260.01 (3.83)
November dummy		-152.48 (1.26)	-152.41 (3.34)
December dummy		-65.49 (1.28)	-65.2 (4.21)
Price coefficients of demand			
Same price in peak	$\bar{\beta}_p$	-201.19 (223.1)	-230.24 (572.5)
Same price in off-peak	$\bar{\beta}_o$	-1688.97 (116.77)	-1720.8 (280.0)
Cross-price	$\bar{\theta}$	119.18 (114.36)	140.06 (273.97)

Table 3, continued Variable	Parameter	Estimate (standard errors in parentheses)	
		1	2
Variance terms			
Variance in y-intercept of peak demand	ω_{11}	955.5 (321.9)	951.6 (684.7)
Variance in y-intercept of off-peak demand	ω_{22}	1628.0 (204.3)	1696.7) (414.5)
Variance in same-price coefficient of peak demand	ω_{33}	3449.7 (1580)	5783.6 (32507)
Variance in same-price coefficient of off-peak demand	ω_{44}	.817 (19529)	.982 (40241)

Table 4

IMPACTS OF OPTIONAL TOU RATES

	D7	D-8C	D-8D	D-8E	D-8G
Proportion who chose TOU	.1130	.1251	.1455	.0574	.1044
I. Average consumption under standard rates					
Customers who chose TOU rates					
Peak (kWh/month)	184.9	176.6	171.8	195.5	186.9
Off-peak (kWh/month)	872.0	841.1	805.9	926.4	857
Customers who chose standard rates					
Peak (kWh/month)	192.4	188.2	178	206.2	213.2
Off-peak (kWh/month)	816.1	811.9	783.6	868.5	881.8
II. Average elasticities					
Customers who chose TOU rates					
Peak: same price	-.149	-.159	-.167	-.129	-.151
Peak: cross price	.088	.094	.098	.076	.089
Off-peak: same price	-.239	-.252	-.275	-.214	-.241
Off-peak: cross price	.017	.018	.019	.015	.017
Customers who chose standard rates					
Peak: same price	-.136	-.148	-.147	-.124	-.136
Peak: cross price	.08	.088	.087	.073	.080
Off-peak: same price	-.253	-.263	-.267	-.224	-.227
Off-peak: cross price	.018	.019	.019	.016	.016
III. Impacts of TOU on customers who chose TOU rates					
Change in consumption					
Peak (kWh/month)	-18.84	-15.18	-17.41	-13.04	-17.77
Off-peak (kWh/month)	55.01	59.48	73.65	36.75	51.95
Change in bill (dollars/month)	-2.25	-6.80	1.58	-0.09	-2.59
Change in utility costs (dollars/month)	0.54	1.00	1.06	0.31	0.52
Change in utility profits (dollars/month)	-2.79	-7.80	0.52	-0.40	-3.11
Change in consumer surplus (dollars/month)	4.54	9.96	2.03	1.81	4.86
Change in total surplus (dollars/month)	1.75	2.16	2.55	1.41	1.75