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IMPACT OF A RESIDENTIAL TIME OF USE RATE ON PEAK, OFF-PEAK AND TOTAL ENERGY CONSUMPTION

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ABSTRACT
This study evaluates the impact of a residential time of use rate pilot implemented by BC Hydro in which customers were randomly assigned to the control group of one of seven treatment groups. There are three main findings as follows. There are three main findings as follows. First, we compared BC Hydro's rate design with 29 TOU rates offered by 24 utilities. This comparison suggests that BC Hydro's set of TOU rates is reflective of standard utility practice in rate design. Second, using hourly metered energy consumption we found that average off peak consumption for the treatment group was 3.2% lower than that for the control group, average on-peak consumption for the treatment group was 11.1% lower than for the control, and average total consumption for the treatment group was 5.5% lower than that for the control group. Third, we found that the estimated elasticity of substitution was 0.06, was very well determined in a statistical sense, but it was substantially lower than for other utilities, which suggests that the possibilities for peak shifting in a winter peaking utility are lower than the possibilities for peak shifting in a summer peaking utility.

KEY WORDS
Time of use rates, electricity demand, energy conservation, elasticity of substitution.

1. Introduction

BC Hydro is a winter peaking utility with substantial energy storage capacity in its hydro-electric reservoirs. The winter peak is due to the widespread use of electric space heating. In recent years, BC Hydro has been energy constrained and consequently imported a significant share of its energy requirements from other utilities. The system as whole has not been demand constrained, although some substations and feeders are nearing their operational capacities. Interest in time-varying rates at BC Hydro therefore stems as much from interest in energy impacts as well as the demand impacts which are perhaps more important for many other utilities.

As part of BC Hydro's Advanced Metering Initiative (AMI), a Conservation Rate Initiative (CRI) time of use rate pilot was developed with 1,950 residential customers for the winter of 2006/07 and 1,717 residential customers for the winter of 2007/08. Customers participating in the pilot had an advanced meter installed at their house, which reported interval data on their demand and consumption on an hourly basis. Customers were randomly assigned to a control group or one of several treatment groups. Treatment group customers received information on how they could save energy during the peak period and shift load from the peak period to the off peak period, and they had access to the CRI website for consumption information for their account.

The goal of the pilot was to determine whether customers respond to pricing signals and information on energy use and to determine the magnitude of the responses. More specifically, the time of use rate pilot provided BC Hydro with the opportunities to: (1) learn about customers' pricing preferences and their responses to pricing signals; (2) assess whether pricing can be used as a tool to delay future supply needs and infrastructure investments; and (3) gain operational experience with advanced metering infrastructure. For residential customers, the residential time of use pilot offered: (1) more rate options; (2) more control over electricity costs; and (3) potential savings on electricity bills.

2. Study issues and approach

For this study there are three main issues as follows. First, assess BC Hydro's rate design against those of a sample of other utilities' time of use rates. Second, evaluate the impact of the time of use rate on off-peak energy consumption, on-peak energy consumption and total energy consumption. Third, estimate the elasticity of substitution between on-peak and off-peak energy consumption.

The study used a variety of methods including random assignment of participating customers to different TOU rate groups, different communication groups and control groups, interviews with project staff, documents review, focus groups (Rink [1], Rink & Mould [2]), pre and post customer surveys addressing energy and conservation behaviours (Pedersen [3]), and econometric analyses in order to assess and understand customers' pricing preferences and their responses to pricing signals (Tiedemann [4]).

Participants were randomly assigned to one of the treatment groups or the control group in three different municipalities in three different regions. This means that there should be no significant market effects, such as free riders or self selection, affecting the internal validity of the experiment. By using treatment and control groups in regions that are reasonably homogenous with respect to heating requirements, as measured by heating degree-days, there is no need to weather normalize the data. Only single family dwellings were considered for participation because of the confounding impact of common walls in multifamily dwellings. All participating customers had an advanced meter installed, whether they were participants or control group members. The operational experience with the AMI meters and advanced technology systems gained through the first year of the pilot was reviewed through interviews with program staff and stakeholders and focus groups with participating customers.

The majority of the behavioural questions in the participant surveys are based on four-point scales (always, usually, occasionally, never). For any behaviour, statistical testing focuses on the top-two box score (proportion always plus proportion usually). Given random assignment to groups and the relatively large sample sizes for each group, the assumption of equal pre-pilot scores is justified, thus allowing the use of z-tests for the difference in the post survey treatment and control group proportions, based on the pooled variance.

Hourly metered data was used to calculate average peak period consumption, average off peak consumption, average total consumption and the ratio of consumption during the peak period to consumption during the off peak period. These statistics were calculated separately for each customer in the control group and for each of the treatment groups in each of the three regions, and they were used to calculate differences between treatment group and control group consumption. Summary statistics were calculated across regions by weighting regional results by the ratio of the regional sample to the total sample. Although there was no pre-program metering, this is viewed as a strong research design because of random assignment to the control or treatment groups. The post-only design with a control group is largely immune to the internal threats to validity that are typically an issue when a non-equivalent comparison group must be used instead of a true control group.

3. Model and estimation

We develop a simple model of a customer's decision of how much electricity to consume during the peak and off-peak periods and use this model to motivate the empirical work. Consider a residential customer with preferences between off-peak energy consumption (denoted by C^O) and peak energy consumption (denoted by C^P) who has the sub-utility function for energy $U(C^O, C^P)$. We write the partial derivative of the utility function U with respect to C^O as U_0 and the partial derivative of U with respect to C^P as U_P. In examining the relationship between off-peak and peak energy consumption, the critical parameter is the elasticity of substitution. Formally, the elasticity of substitution υ measures the percentage change in the proportion of peak and off-peak energy consumed due to a change in the marginal rate of substitution

$$(1)\ \upsilon = dln(C^O/C^P)/dln(U_P/U_O)$$

or expanding this expression we have

$$(2)\ \upsilon = [d(C^O/C^P)/d(U_P/U_O)]\cdot[(U_P/U_O)/(C^O/C^P)]$$

The elasticity of substitution measures the ease with which off-peak energy can be substituted for peak energy, and vice versa. The elasticity of substitution is essentially a measure of the curvature of an indifference curve. In other words, the more curved or convex is the indifference curve, the smaller is the elasticity of substitution. If there is no substitution between peak and off-peak energy (that is, the indifference curves are L-shaped), the elasticity of substitution is zero. If there is perfect substitution between peak and off-peak energy, (that is the indifference curves are straight lines), then the elasticity of substitution is infinity. Consider now a residential customer with preferences between off-peak and peak energy consumption who has the sub-utility function for energy $U(C^O, C^P)$ which takes the standard constant elasticity of substitution (CES) form as follows

$$(3)\ U(C^O, C^P) = [\omega(C^O)^{-\eta} + (1 - \omega)(C^P)^{-\eta}]^{-1/\eta}$$

Here the parameter η determines the elasticity of substitution which is given by the expression

$$(4)\ \upsilon = 1/(1 + \eta)$$

and ω is a weight. Assuming standard two-stage budgeting, the customer maximizes her utility subject to her budget constraint for energy.

$$(5)\ C^O p^O + C^P p^P \le I^e$$

And this yields the following first-order condition:

$$(6)\ P \equiv p^P/p^O = [(1 - \omega)/\omega]\ [C^P/C^O]^{1+\eta}$$

This first-order condition can be rewritten as follows:

$$(7)\ C^P/C^O = [(\omega/(1 - \omega))\ P]^{\upsilon}$$

Finally, taking logs of both sides yields the estimating equation,

$$(8)\ ln(C^P/C^O) = \alpha_0 + \alpha_1\ ln(P)$$

where, $\alpha_0 = - \upsilon \ln((1 - \omega)/\omega)$ and $\alpha_1 = - \upsilon$.

We turn next to the estimation procedure employed (Wedderburn [13], [14], [15]). A GLM is a linear model for the transformed mean of a variable which has distribution in the natural exponential family. The generalized linear model is characterized by three components: a random component which specifies the response function of the dependent variable; a systematic component which specifies a linear function of independent variables which is used as a predictor; and a link component which specifies the functional relationship between the systematic component and the expected value of the random component. We follow the exposition in Agresti [16], but see also Dobson [17], McCullagh and Nelder [18], McFadden [19], 920, and [21].

The first component of GLM is called the random component. Suppose that we have N independent observations from a distribution which is a member of the natural exponential family, and we write this as $y = (y_1, \ldots, y_N)$. Suppose further that y_i has the probability function

$$f(y_i; \theta_i; \varphi) = exp\{[y_i\, g(\mu_i) - b(\theta_i)]/a(\varphi) + c(y_i, \varphi)\}.$$

The parameter θ_i is called the natural parameter, and the parameter φ is called the dispersion parameter. In many cases, the function $a(\varphi)$ takes the form $a(\varphi) = \varphi/\omega_i$ for known weight ω_i. For example, if y_i is the mean of N_i independent observations, it is natural to set $\omega_i = n_i$.

The second component of GLM is called the systematic component. Suppose $x_{i1}, \ldots, x_{it}$ represents the ith observation on at-vector of independent variables. Then the systematic component is the linear predictor

$$\eta_i = \Sigma_j \beta_j x_{ij},\ i = 1, \ldots, N.$$

The third component is called the link function, which links the expected value of the response vraible to the explanatory varianles as follows

$$\eta_i = g(\mu_i) = \Sigma_j \beta_j x_{ij}.$$

The function g for which $g(\mu_i) = \theta_i$ is refereed to as the canonical link because in this case there is the following direct relationship between the natural parameter and the linear predictor

$$\theta_i = \Sigma_j \beta_j x_{ij}.$$

Estimation proceeds in the obvious way. For N independent observations, the log likelihood function is given by

$$L(\beta_1, \ldots, \beta_t) = \Sigma_i \log f(y_i; \theta_i; \varphi) = \Sigma_i l_i,$$

where $l_i = l(y_i; \theta_i; \varphi)$.

To obtain the likelihood equations we maximize each l_i with respect to β_i, using the method Fisher scoring which is essentially the Newton-Raphson method but where Fisher scoring uses the expected value of the matrix of second derivatives.

4. Rate design

The main rate design principles used in developing the TOU pilot rates were as follows: encourage economic efficiency; minimize impacts on other rate payers, by using a rate design that is customer revenue neutral and that collects the revenue requirement; use TOU daily peak periods that are short in duration, simple for customers to use, and easy to administer; and, select a rate design that is fair and avoids windfall gains or losses to customers.

The rate attributes and structure are as follows: first, the rate is a voluntary rate with customers choosing whether or not to participate in the experiment; and second, the TOU rate has a two-part rate structure, which includes a basic charge, energy charges based on TOU prices, a balancing amount and a bill guarantee. In order to test a reasonable range of rate alternatives, there are seven experimental rates (T1 – T7) and one control rate (C). The rates vary by number of peaks, by peak rate, by off-peak rate and by critical peak price rate as shown in Table 1 below. Campbell River on Vancouver had both a morning and an evening peak rate while Fort St. John in the north and the Lower Mainland in the southwest had only an evening peak rate. The reason for this feature of the design is that Vancouver Island experiences both a morning and an evening peak in the winter because of the widespread use of electric space heating, while the rest of British Columbia has only an evening peak.

Table 1: BC Hydro Winter Weekday TOU Pilot Rate Design

Group	Morning peak	Evening peak	Off peak (¢/kWh)	Peak (¢/kWh)	Critical (¢/kWh)
T1	-	4-9 pm	6.33	19.0	-
T2	-	4-8 pm	6.33	19.0	-
T3	-	4-9 pm	6.33	19.0	50.0
T4	-	4-9 pm	6.33	25.0	-
T5	-	4-9 pm	4.5	28.0	-
T6	8-11 am	4-8 pm	4.5	15.0	-
T7	8-11 am	4-8 pm	4.5	15.0	50.0
C	-	-	6.33	6.33	-

A number of utilities have undertaken TOU rate pilots for residential, commercial and industrial customers, while some utilities have put in place mandatory TOU rates, particularly for larger customers. A substantial literature has examined the impacts of these TOU rates, and some references include Aigner and L. Lillard [5], Braithwait [6], Caves, Christensen and Herriges [7], Charles River Associates [8], Faruqui and George [9], King [10], New York: Federal Energy Regulatory Commission [11], and Woo [12]. Key findings of these studies include the following: (1) customers respond to TOU rates by shifting peak, reducing consumption or some combination of the two; (2) since the peak shifting or consumption change to a price differential is relatively small, relatively large peak to off peak price ratios are required to have significant impacts; (3) permanent TOU rates have larger impacts than experimental (or temporary) rates; (4) demand charges can have effects comparable in size to TOU rates; and (5) enabling strategies such as promotion of load shifting technologies can substantially increase the impact of TOU rates.

We reviewed a number of other studies focusing on residential TOU rates for utilities with at least one million customers, including a comparison with the BC Hydro TOU rates. This information was used to build a database of some 29 residential customer TOU rates offered by 24 utilities. Some key observations from this review include the following, where all numbers are in U.S. cents. (1) Median peak rate is 16.07 cents per kWh, which is just below BC Hydro's lowest peak rate of 16.15 cents per kWh. (2) Median off peak rate is 3.66 cents per kWh, which again is just below BC Hydro's lowest off peak rate of 3.82 cents per kWh. (3) Median peak to off peak ratio is 3.6, which is between BC Hydro's two lower peak to off peak ratios of 3.0 and 4.0. (4) Median monthly charge is $6.12, compared to BC Hydro which has a monthly charge of $3.14 for all residential rates. This comparison suggests that BC Hydro's set of TOU rates is reflective of standard utility practice in rate design.

5. Energy impacts

For each account participating in the time of use experiment, hourly consumption information was cleaned and then aggregated to daily consumption for the off-peak period, the peak period and the daily total, for each of the 120 days of the CRI experiment. About 1% of the readings were corrupted in the sense that there were missing hourly values with the metering then catching up and reporting the total for several hours for that meter. Statistically based algorithms were built to allocate this load across the appropriate hours as accurately as possible. For each rate class for each region, the consumption data for peak, off-peak and total was aggregated and then averaged to produce daily average consumption for the appropriate customer bin. Finally, the treatment groups in a given region were averaged, and the average daily consumption for each bin was compared with the appropriate daily consumption for the appropriate control bin.

Table 2 provides information on the impacts for the three regions in the pilot and for the pilot as a whole. As noted above, Campbell River had both morning and evening peak rates because it experiences both a morning peak and an evening peak in the winter. The impacts of the time of use rate for the second year can be summarized as follows. (1) Impact on Off-peak Consumption. Weighted average off-peak consumption for time of use rate treatment participants was 26.99 kWh per day compared to control group off-peak consumption of 27.88 kWh per day. The average off peak consumption of a treatment group participant was 0.89 kWh per day or 3.2% lower than that of the average control group participant. (2) Impact on Peak Consumption. Weighted average peak consumption for time of use rate treatment participants was 10.16 kWh per day compared to control group peak consumption of 11.43 kWh per day. The average peak consumption of a treatment group participant was 1.27 kWh per day or 11.1% lower than that of the average control group participant. (3) Impact on Average Daily Consumption. Weighted average total consumption for time of use rate treatment participants was 37.15 kWh per day compared to control group total consumption of 39.31 kWh per day. The average total consumption of a treatment group participant was 2.16 kWh per day or 5.5% lower than that of the average control group participant.

Table 2: Time of Use Rate Energy Impacts

	Control (kWh/day)	**Treatment (kWh/day)**	**Difference (kWh/day)**	**Difference (%)**
Campbell River				
Av daily off-peak	40.33	38.18	-2.15	-5.3%
Av morning peak	8.93	7.21	-1.72	-19.3%
Av evening peak	12.07	10.95	-1.12	-9.3%
Av total daily peak	21.00	18.16	-2.84	-13.5%
Av daily total	61.33	56.34	-4.99	-8.1%
Fort St. John				
Av daily off-peak	30.92	24.79	-6.13	-19.8%
Av daily peak	10.59	8.43	-2.16	-20.4%
Av daily total	41.51	33.22	-8.29	-20.0%
Lower Mainland				
Av daily peak	23.55	23.26	-0.29	-1.2%
Av daily off-peak	9.31	8.25	-1.06	-11.4%
Av daily total	32.86	31.51	-1.35	-4.1%
Weighted Total				
Av daily off-peak	27.88	26.99	-0.89	-3.2%
Av daily morn peak	1.44	1.30	-0.14	-9.7%
Av daily evening peak	9.99	8.86	-1.13	-11.3%
Total av daily peak	11.43	10.16	-1.27	-11.1%
Av daily total	39.31	37.15	-2.16	-5.5%

6. Elasticity of substitution

We estimate the elasticity of substitution using generalized estimating equations (Wedderburn [13], [14], [15]). Generalized estimating equations are often applied when there are repeated measures on each observational unit, so that the assumptions underlying least squares estimation are not appropriate. In particular, generalized estimating equations allow for the possibility that error terms are not necessarily normally distributed and error terms are not necessarily independent.

Table 3 provides the results of the generalized estimating equations modelling. The standard errors for the coefficients are shown in parentheses, and the level of statistical significance is indicated by the number of asterisks where one, two or three asterisks means that the coefficient is significant at the 10%, 5% or 1% level respectively. We use three different specifications, and we note that most regressions are significant at the 1% level. For each estimated equation, the elasticity of substitution is the negative of -0.06 or 0.06, and it is well determined. This value of the elasticity of substitution between peak and off-peak consumption is very low but it is consistent with the literature. A low value of the elasticity of substitution means that customer's ability to shift load from the peak to the off-peak period is quite limited.

Table 3: Elasticity of Substitution

Parameter	Equation 1	Equation 2	Equation 3
Constant	-0.947*** (0.144)	-0.987*** (0.112)	0.958*** (0.123)
Log (peak/off-peak price)	-0.061*** (0.013)	-0.060*** (0.012)	-0.060*** (0.012)
Log HDD	-0.027** (0.016)	-0.033*** (0.007)	-0.044*** (0.015)
Log household income	0.014 (0.012)	0.032*** (0.011)	0.032*** (0.011)
Log occupants	0.015 (0.017)	0.049*** (0.015)	0.049*** (0.015)
Lower Mainland region	-	-0.325*** (0.022)	-0.423*** (0.047)
Fort St. John region	-	-0.367*** (0.028)	-0.141** (0.068)
LM*log HDD	-	-	0.038** (0.017)
FSJ* log HDD	-	-	-0.066*** (0.021)
Electric baseboards	0.082*** (0.029)	0.114*** (0.027)	0.114*** (0.027)
Not a CPP day	-0.025 (0.024)	0.071*** (0.024)	0.072*** (0.023)
Scale Parameter	0.180	0.164	0.164

Note. One, two or three asterisks means that the coefficient is significant at the 10%, 5% or 1% level respectively.

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7. Summary and conclusion

The purpose of this paper is to summarize the objectives, methods and results of the process and impact evaluation of the second year of the Conservation Rate Initiative (CRI) project. The experiment involved 1,717 residential electricity customers who were randomly assigned to one of seven treatment groups or to a control group. All participants in the experiment had special meters installed which provided hourly information on their electricity consumption.

There are three main findings for this study. First, we compared BC Hydro's rate design with 29 TOU rates offered by 24 utilities. This comparison suggests that BC Hydro's set of TOU rates is reflective of standard utility rate design practice. Second, using hourly metered energy consumption we found that average off peak consumption for the treatment group was 3.2% lower than that for the control group, average on-peak consumption for the treatment group was 11.1% lower than for the control, and average total consumption for the treatment group was 5.5% lower than that for the control group. Third, we found that the estimated elasticity of substitution was 0.06, that it was very well determined in a statistical sense, but it was substantially lower than for other utilities, which suggests that the possibilities for peak shifting in a winter peaking utility are lower than the possibilities for peak shifting in a summer peaking utility.

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