Estimating the Consumption Impact of a Residential Conservation Program

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A residential water heating program in a Western utility offers a rebate to its customers who buy efficient gas water heaters. In the current paper we carry out a pre-post comparison of water heating efficiency for consumers who participated in the program. In addition, we test to see whether the nonparticipants have water heating consumption patterns that differ from the participants before they install the new water heaters. The experiment is carried out in the context of a monthly natural gas conditional demand estimation procedure that contains submodels of therm use through water heaters, space heaters and other gas appliances. The data set consists of pooled time-series/cross-section information on participants and nonparticipants. The estimation data set contains 102,157 pooled observations. Overall, the statistical fit of the equation seems reasonable (R square = .80) and the t-ratios for the variables in the model are generally quite large. The model contains a coefficient that is used to estimate the pre-post rebate water heating efficiency change presented in the text.

Introduction

This report summarizes the work to date on an econometric study of the first-year impacts of a residential demand-side management program in the Western U.S. The program impacts we discuss here are based on the conditional demand technique. The goals of the current research are:

1. to estimate the first-year impact of a residential conservation program; and,

2. to provide the analytical tools for a market segmentation analysis which can be used to target programs to groups of customers where the promise of energy savings is greatest.

The focus of the analytical work for this study is on measuring the first-year impact of a residential appliance rebate program. This program encourages the purchase of gas-fired water heaters that exceed current efficiency standards. The measurement task consists of estimating the effect of installed higher efficiency equipment on natural gas usage.

This report is organized as follows: the general technical approach, the analytical data set, the conditional demand regression results, and a summary of the results.

Technical Approach

In this section we will first discuss the general conditional demand setting of our analysis and then describe the thermodynamic relationships underlying our analysis. After this we will discuss briefly our method for quantifying program impacts.

The Conditional Demand Equation

The hallmark of a conditional demand equation is its end-use orientation. Following Parti and Parti (1980) we write the conditional demand equation for natural gas as the sum of the gas energy used through the appliances connected to the gas meter. The time unit for the current analysis is one month and the equation we use for our current modeling effort is as follows.

$$\begin{aligned} Therms = {} & gWH * [WaterHeaterIndicator] \\ & + gSH * [SpaceHeaterIndicator] \\ & + gOTHER \end{aligned} \tag{1}$$

where **Therms** is the number of therms used per *normalized month*, **gWH** is the gas used through the water heater, **gSH** is the gas used through the space heater, **gOTHER** is the gas used for other appliances (ranges, dryers, etc.); and the water/space heater indicator variables are each one if the corresponding heater is connected to the gas meter, and zero if not. We use the term *normalized month* to indicate that we divide the number of therms by the number of days in the bill reading period and then multiply by 30.4 (=365/12), the average number of days per month.

The data set upon which our analysis is based contains pooled cross-section and time-series elements. Accordingly, our estimation procedure is designed to deal both with first-order serial correlation and cross-sectional differences in the error variance (heteroskedasticity). A multi-stage procedure is employed to construct the generalized difference terms that is used to deal with the serial correlation issue, and the Prais-Houthakker procedure is used to account for the household-to-household differences in the error variance (see Maddala 1977).

The water and space heating portions of the equation, **gWH** and **gSH** are modeled in some detail. The **gOther** energy consumption is simply modeled, however, as an appliance stock variable; i.e., a sum of appliance-specific expected consumption amounts, each multiplied by the corresponding appliance indicator variable.

Water Heating Energy Use

In our thermodynamic structure, water heating consumption consists of a standby loss component and a replacement water use component. The replacement water heater use component results from the daily hot water use by household occupants. As they take showers and wash dishes, the hot water they use is replaced in the tank by water that must be heated from the ground water temperature to the tank temperature. The magnitude of this component depends primarily upon the number of household occupants and the difference between the temperature of the water they use and the ground water temperature.

The standby loss component results from the escape of heat from the water heater tank. For a given amount of tank insulation, the magnitude of this component depends upon the tank size and the difference between the internal temperature of the water heater tank and the air temperature around the tank.

Both of these components of the load can be affected by increasing the burner efficiency. The energy used for the water heater is modeled as follows:

$$gWH = SB + R \qquad (2)$$

where SB is the standby loss for the water heater and R represents the energy used to heat the water replacing the heated water used by the consumer. Apart from an efficiency factor to be discussed below, the engineering estimate of the standby loss, **SB'**, is computed using the following relationship:

$$SB' = UAw * (Th - Ta) \qquad (3)$$

where **UAw** is the area-conductance product of the water heater, **Th** is the temperature of the heated water in the tank, and **Ta** is the temperature of the air surrounding the water heater.

Apart from an efficiency factor, our engineering estimate of the replacement water energy use is computed using the following relationship;

$$R' = c * (Th - Tc) * Lh \qquad (4)$$

where **c** is the number of BTU's required to raise a gallon of water one degree, **Th** is the temperature of the hot water in the water heater, **Tc** is the ground water temperature and **Lh** is the number of gallons of hot water used per month. From the water heating point-of-view, of course, **Lh** is also the number of gallons of water heated by the water heater to **Th** to replace the water used for showers, etc.

Although we use equation (4) for our analysis, it would be possible to express the model in terms of the temperature of the water actually used by consumers rather than the unmixed hot water from the water heater tank. Interestingly, it can be shown that equation (4) can equivalently be written as follows

$$R' = c * (T - Tc) * L \qquad (4a)$$

where, **T** is the temperature of the water actually used by consumers for showers, etc.; and **L** is the total number of gallons of mixed hot and cold water used by consumers.

The engineering estimate of total water heating use, apart from an efficiency factor, is therefore computed using the following relationship

$$gWH' = UAw * (Th - Ta) + c * (Th - Tc) * Lh \qquad (5)$$

where all units are converted to monthly Therm levels.

Space-Heating Energy Use

The model for space heating energy use is focused upon the effects of variables such as building size and temperature patterns on heat loss. The basic heat loss relationship used in our model can be written

$$gSH = IEs * UAs * HDH \qquad (6)$$

where IEs is the inverse efficiency of the space heater, UAs is an area conductance product for the building estimated from survey data and HDH is an estimate of the sum of the monthly differences between the inside and outside the residence for all the hours of the month when this difference is positive. HDH is measured in units of heating degree-hours.

The Quantification of Savings

Our approach to measurement proceeds on the end-use level by making use of the conditional demand technique. This technique allows us to decompose billing data into estimates of end-use DSM measurement equations. In addition we try to take account of the major thermodynamic factors affecting residential gas consumption so that we do not ignore important interaction effects affecting DSM impacts. The water heating rebate effects that we estimate are modeled in the water-heating portion of our conditional demand equation.

We test for any post-implementation differences in water heater consumption stemming from the installation of more efficient water heaters by including a post-implementation term for households that installed efficient water heaters under the rebate program. Neglecting the regression equation error term, but including the water heater efficiency term explicitly, the resulting model can be represented as follows:

$$gWh = b * [IEw * gWh'] \tag{7}$$

where IEw is the inverse efficiency of the water heater, gWh' is an engineering estimate of expected water heating given the size of the water heater tank, the number of household occupants, and several temperature variables. b is a coefficient that is estimated in the conditional demand equation and is used to calibrate the engineering estimate of water heater use to the actual household consumption.

Now, the efficiency of the water heater is not constant in our sample for the households that acquired efficient water heaters. In fact, we can write an equation for the efficiency term as follows:

$$IEw = IEw0 + Dif*IMP \tag{8}$$

where IEw0 is the pre-implementation inverse water heater efficiency, Dif is the change in inverse water heater efficiency stemming from an installation of a new water heater undertaken under a rebate program, and, IMP is a 0-1 binary variable indicating whether a new water heater has been installed in the current month. In this connection, note that all gas consumption in our model refers to a specific month even though we have not stressed that by using an explicit time subscript on our variables.

If we substitute equation (8) into equation (7), we obtain

$$gWh = b * [(IEw0 + Dif * IMP)(gWh')] \tag{9}$$

or,

$$gWh = b * [IEw0 * gWh'] + (b * Dif) * [(IMP) * (gWh')] \tag{10}$$

In our conditional demand estimation procedure we let

$$b' = b * Dif \tag{11}$$

and estimate the following equation

$$gWh = b * [IEw0 * gWh'] + b' * [IMP * gWh'] \tag{12}$$

The post rebate savings variable in our regression equation is calculated as [IMP * gWh'], the second term in brackets in equation (12).

As noted above, the b is a coefficient that calibrates the engineering estimate of water heater consumption to the observed consumption. Using equation (11) to solve for the difference in inverse efficiency after the installation of the new water heaters, we have

$$Dif = b'/b \tag{13}$$

The Data Set

This section contains a description of the analytical data set on which we base our study. The data set used in this analysis contains information on rebate participants and nonparticipants. For the participants we estimate a base load and a DSM saving increment based upon their characteristics, the weather and (for the savings) the efficient water heaters they bought under the rebate program. Using this information, we quantify the pre-post program implementation impacts for these customers, after taking account of the interaction effects of weather, the water heater tank size, the building size, the number of occupants and other relevant variables.

The analytical data set we use for this analysis consists of four sample elements acquired from different sources: survey responses, billing information, program implementation data, and weather. The four sample elements contributed the following kinds of information. From the survey responses, we learned what types of appliances are in use in each household, some information about conservation measures taken and attitudes toward them, and a variety of details about the composition of the household. The billing data contribute observations over time of each household's consumption of gas. The program implementation data supply the dates on which respondents implemented the rebate purchases, along with additional details about the residence. The weather data allow calculation of temperature variables (average temperature and heating-degree-hours) facing each household for each consumption period.

The survey data set contains appliance ownership and other demographic information on 5647 households. The billing and weather data sets contained monthly information on natural gas consumption and weather data, respectively, that spanned the 1990 to 1991 period. After eliminating observations with missing information, our combined time-series/cross-section sample size for the regression procedure was 102,157.

The data sets described in this section are the basis of the empirical work performed for this study. In the next section we discuss the conditional demand results based upon these data.

The Regression Results

In this section we will discuss the conditional demand regression results that are used in our quantification of program impacts. As noted in the Technical Approach section, the overall conditional demand equation is the sum of the end-use gas equations. The appliances modeled in detail in this equation are gas space heaters and water heaters. In addition, we include an appliance stock variable to account for the remainder of the residential natural gas appliances: clothes dryers, pool and spa heaters, barbecues, fireplaces and gas ranges.

The goodness-of-fit characteristics of the equation are generally quite good with the overall R^2 =.80 and the t-values for the important coefficients are generally large. In the conditional demand regression equation, the gas space heaters and water heaters are modeled using detailed thermodynamic relationships. As noted in the Introduction, the space heater is modeled as depending primarily on the size of the house and the monthly heating degree-hours. In addition, the model takes into account differences in degree-day sensitivity between multifamily and other dwelling types, and an incremental degree-day sensitivity in the Winter months. We have tested similar terms for differences between the water heater rebate participants and nonparticipants and have found no significant differences.

In general, the t-values for the coefficients for the space heating model are quite large, ranging in absolute value from 17 to 72. Such high t-ratios are due, at least in part to the large sample size, and the great care devoted to data preparation. The fundamental heat-loss estimate for the model is .7261 times the engineering estimate; although during the Winter months, the estimated heat-loss is 1.09 (=.7261+.3681) times the engineering estimate. In addition, the fundamental heat loss for multi-family is lower than that for other dwellings by a factor of .2132 times the engineering estimate.

As noted above, the water heater consumption is modeled as the sum of a standby loss and a replacement water use. We use an engineering model to summarize these components, and then estimate a coefficient to calibrate the engineering model to metered customer consumption in the conditional demand equation.

We calibrate the model of base water heating use separately for participant and nonparticipant customer groups to test whether there are any differences in the determinants of water heating consumption across our sample. We estimate that the appliance rebate customers consume 157% of what would be predicted by the engineering model. Interestingly, the nonparticipants are somewhat higher users in this group since they are estimated to consume 175% of what would be predicted from the engineering model on the basis of their water tank sizes and the number of occupants in the houses. As in the case of the space heating model, the t-ratios in this water heating submodel are large.

To test for any post implementation differences in water heater consumption stemming from the installation of more efficient water heaters, we included a post implementation term, **Post Rebate**, for households who installed efficient water heaters under the rebate program. The coefficient of this term, -.2577, is used to calculate the inverse efficiency differences associated with the purchase of efficient water heaters under the rebate program. This inverse efficiency difference is negative and is calculated as -.1641. Of course, a negative effect on the inverse efficiency corresponds to a positive effect on efficiency itself. The details of this calculation are presented in the Technical Approach section.

The remainder of the end uses have been modeled in less detail as an appliance stock variable that is a weighted sum of the remaining end-use appliance indicator variables.

Summary

The work performed to date has been focused upon

1. estimating a basic conditional demand equation that can be used to model residential end-use natural gas consumption; and then,

2. employing this basic end-use model to test for rebate implementation impacts; and differences in the consumption patterns of program participants and non-participants.

In our conditional demand analysis we have modeled the space and water heating end uses in greatest detail, although all the major residential gas appliances are accounted for in the equation. The impact analysis has thus far been performed for water heating. For this case we have estimated an impact of a 0.1641 difference in the inverse efficiency of the water heater stemming from purchases made in connection with the rebate program. Furthermore we have tested for differences in consumption patterns among program participants and non-participants and have found that the nonparticipants consume more water heating energy than the participant group before the rebate implementation, holding constant the effects of variables such as water heater tank size and household occupancy. Because of household-to-household differences, the savings estimated for the participants may differ from the savings that nonparticipants would get from similar implementations. The base load equations for the nonparticipants can be used to obtain preliminary estimates of the potential savings impacts for that group. Of course, such estimates would have to be regarded as preliminary since there may exist behavioral differences between participants and nonparticipants that depend upon differences in tastes, perceptions or attitudes for which we do not account in our model.

References

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Table 1. Regression Results

DEPENDENT VARIABLE: Therms
ADJUSTED RSQUARE: 0.80
Observations: 102,157

Category/Variable	Coefficient	t-Ratio
Gas Space Heater		
Heat Loss (UA*HDD)	0.7261	71,5243
Heat Loss Increment for multifamily	-0.2132	-17.3216
Heat Loss Increment for Winter	0.3681	47.3620
Gas Water Heating		
Base Energy Use:		
Rebate Group	1.5702	64.3712
Non-Rebate Group	1.7461	74.8249
Savings:		
Post Rebate	-0.2577	-8.4361
Other Appliance Stock	0.9534	82.3978