ABSTRACT
In response to increasing concerns about the potential impacts of energy sector greenhouse gas emissions, policy makers have supported various instruments to increase energy efficiency and reduce energy consumption. One such instrument is the voluntary Energy Star program which develops and promotes standards and labelling for energy efficient products, including residential appliances. This paper provides the results of a detailed evaluation of BC Hydro’s Energy Star appliance program for its first twenty-six months of operation, using data from engineering field studies and time-series modelling. The paper has three main findings. First, the program resulted in the purchase of an additional 26,778 Energy Star refrigerators and an additional 32,452 Energy Star clothes washers. Second, the additional Energy Star refrigerators saved 1.6 GWh of electricity per year and the additional Energy Star clothes washers saved 6.1 GWh of electricity per year. Third, the additional Energy Star refrigerators reduced peak demand by 0.51 MW and the additional Energy Star clothes washers reduced peak demand by 1.91 MW.

KEY WORDS
Time-series modelling, regression analysis, identification, energy efficiency.

1. Introduction

Many observers believe that anthropogenic greenhouse gas emissions, including carbon dioxide, are the major cause of medium-term climate change. Since about two-thirds of greenhouse gas emissions are due to activities in the energy sector, reducing energy sector greenhouse emissions is viewed by many as critical in slowing the rate of increase in average global temperature. Policies aimed at reducing energy sector greenhouse gas emissions include reducing emissions from existing power generation facilities, developing new power generation sources with lower emissions, increasing energy prices to reduce energy consumption, and increasing end use energy efficiency.

Utilities, utility regulators, federal governments, state and provincial governments, and local and municipal governments in Canada and the United States have supported the voluntary Energy Star labelling program as one method of promoting the purchase and installation of energy efficient appliances and equipment. This support has included the development of appropriate standards and test procedures, advertising and other promotional activity, and financial incentives to reduce the initial cost of energy efficient appliances and equipment.

Studies of the development, scope and impacts of Energy Star include [1]-[22]. Despite the substantial size of this literature, few published studies have estimated the impact of financial incentives on the purchase and installation of Energy Star qualifying household appliances or the consequent impact on energy consumption using appropriate statistical modelling procedures. The purpose of this study is to help fill this gap by using appropriate engineering field measurement combined with appropriate time-series modelling to estimate the impact of a utility Energy Star residential appliance program. The paper makes two main contributions. First, it is one of the few published studies to use detailed engineering field measurements to estimate unit energy and peak demand savings from a residential appliance rebate program. Second, it is also one of the few published studies to use time-series modelling to estimate total energy and peak demand savings from a residential appliance program.

An overview of the paper is as follows. Section 2 summarizes the Energy Star Appliance program and presents the data and methods used, including summaries of the engineering field work and the statistical modelling. Section 3 presents the study results, including unit energy and peak demand savings and program-level energy and peak demand savings. Section 4 provides the study conclusions.

2. Data and Method

2.1 Program Description

BC Hydro’s Energy Star Appliance program is a multi-year energy acquisition and market transformation program that encourages its residential customers to purchase and use energy-efficient Energy Star appliances.
Table 1

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>EPA introduces the Green Lights program</td>
</tr>
<tr>
<td>1992</td>
<td>Initial products covered by Energy Star include computers, and monitors with printers added in 1993 and fax machines in 1994</td>
</tr>
<tr>
<td>1995</td>
<td>Added products include copiers, residential heating and cooling equipment, thermostats, new homes</td>
</tr>
<tr>
<td>1996</td>
<td>Added products included dishwashers, refrigerators and room air conditioners, with residential light fixtures and clothes washers added in 1997</td>
</tr>
<tr>
<td>1998</td>
<td>Added products included televisions and windows</td>
</tr>
<tr>
<td>1999</td>
<td>Added products included consumer audio and DVD equipment and roofing products</td>
</tr>
<tr>
<td>2001</td>
<td>Canada agrees to partner with U.S. in Energy Star with the subsequent addition of European Union to partnership</td>
</tr>
</tbody>
</table>

From January 2008 through May 2010, BC Hydro’s Energy Star Appliance program offered residential customers a $50 incentive on Energy Star refrigerators and clothes washers. The rebate program was supported by in-store and on-line retailer training, mass media advertising and in-store promotional activity. The Energy Star share of appliance sales in British Columbia increased from 30% in early 2010 to 71% in early 2010.

2.1 Economic Time Series Modelling

Consider the following general linear model

\[ y = X\beta + \varepsilon \]  

(1)

and where \( y \) is a \( T \times 1 \) vector, \( X \) is a \( T \times k \) matrix, \( \beta \) is a \( k \times 1 \) vector, \( \varepsilon \) is a \( T \times 1 \) vector with \( \varepsilon \sim N(0, \sigma^2I) \). Using \( E \) for the expectation operator and noting that \( E\varepsilon = 0 \) since the expectation of each of its components is zero, the sum of the squared errors is defined as \( S \) and the variance of the errors is then the expectation of \( S \)

\[ S = \varepsilon'\varepsilon = (y - X\beta)'(y - X\beta) \quad \text{and} \quad E\varepsilon'\varepsilon = \sigma^2I, \]  

(2)

The ordinary least squares (OLS) estimators of the vector of parameters \( \beta \) and the variance of the errors \( \sigma^2 \) are found by minimizing the sum of the squared errors

\[ \min_{\beta} \varepsilon'\varepsilon = \min_{\beta} (y - X\beta)'(y - X\beta) = 0. \]  

(3)

Solving (4) for \( \beta^* \) the estimated value of \( \beta \) yields the following expression for the OLS estimator

\[ \beta^* = (X'X)^{-1}X'y. \]  

(4)

Economic modelling of time series data sometimes assumes that the error terms are independent between periods or that there is no auto-correlation. But in many cases, errors are correlated over time rather than independent, often due to persistent shocks reflecting the inertia of economic processes. Auto-correlated errors have three main consequences. First, although the estimated ordinary least squares (OLS) errors are unbiased, tests for the statistical significance of the parameters and the associated error bands are not correct. Second, OLS is no longer an efficient method of estimating parameters. Third, OLS is no longer an efficient method of forecasting future values of the dependent variable.

Suppose the errors are now given by the following first-order scheme

\[ \varepsilon_i = \rho \varepsilon_{i-1} + u_i, \quad t = 1, 2, ..., T \]  

(5)

We assume that the absolute value of the parameter \( \rho \) is less than one, the \( u_i \) are independently and identically distributed with variance \( \sigma_u^2 \), and \( \varepsilon_i \) are generated by a stationary stochastic process beginning in the infinite past. This form of the errors is awkward to work with and the calculations can be simplified by expanding the previous expression by making successive substitutions for \( \varepsilon_i \) to yield:

\[ \varepsilon_t = \sum \rho^i u_{i+1}, \]  

(6)

where the sum runs over \( i = 0, 1, ..., \infty \). Using the assumptions on \( u_i \) and the formula for the sum of a converging series gives the variance of \( \varepsilon_i \) as follows:

\[ E(\varepsilon_i^2) = \rho^2 E(u_i^2) + \rho^2(u_i^2) + ... = \sigma_u^2/(1 - \rho^2) = \sigma^2 \]  

(7)

Finally, the covariance of \( \varepsilon_i \) with \( \varepsilon_{i+j} \) is needed, which is:

\[ E(\varepsilon_i\varepsilon_{i+j}) = E([u_i + \rho u_{i+1} + ...][u_{i+j} + \rho u_{i+j+1} + ...]) = \rho^j \sigma_u^2 \]  

(8)

This gives all the variances and covariances in the variance-covariance matrix for \( \varepsilon_i \). Since every term contains \( \sigma_u^2 \), this common term can be extracted and the variance-covariance matrix can be written as follows:
If the value of $\rho$ were known, the value of $\beta$ could be found that minimizes this sum of squares as with for the ordinary least squares estimator to yield the generalized least squares estimator:

$$\beta = (X'\Omega^{-1}X)^{-1}X'\Omega^{-1}y$$  \hspace{1cm} (10)$$

But since the value of $\rho$ is not known, a maximum likelihood estimator can be used, which gives us consistent and asymptotically efficient estimates of the parameters. Start by formulating the likelihood function in the usual way and taking its log which yields:

$$\ln L(y, X, \beta, \sigma_\epsilon^2, \rho) = -T/2 \ln(2\pi) - 1/2 \ln[\sigma_\epsilon^2\Omega] - (2\sigma_\epsilon^2)^{-1/2}y'\Omega^{-1/2}(y - X\beta)$$ \hspace{1cm} (11)$$

This expression can be simplified by partially maximizing with respect to $\beta(\rho)$ and $\sigma_\epsilon^2(\rho)$ which, noting that these expressions are functions of $\rho$, yields the simpler concentrated likelihood function:

$$\ln L^*(\rho, y, X) = -T/2 \{\ln(2\pi) + 1\} - T/2 \ln\{[\sigma_\epsilon^2(\rho)]((1 - \rho^2)^{-1/2})\}$$ \hspace{1cm} (12)$$

Maximizing this function with respect to $\rho$ is then a relatively straightforward numerical estimation problem, using, for example, the method of Gauss-Newton.

### 2.2 Unit Energy and Peak Demand Savings

Unit energy and peak demand savings per appliance were estimated using standard engineering methods following the International Performance, Measurement and Verification Protocol (IPMVP).

#### Table 2

Summary of the International Performance, Measurement and Verification Protocol Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Retrofit isolation: key parameter measurement</td>
<td>Savings are determined by field measurement of the key parameter(s) that define energy use of the efficiency measure</td>
</tr>
<tr>
<td>B. Retrofit isolation: all parameter isolation</td>
<td>Savings are determined by field measurement of the energy use of the affected system</td>
</tr>
<tr>
<td>C. Whole facility</td>
<td>Savings are determined by measuring energy use of the whole facility or of a sub-facility</td>
</tr>
<tr>
<td>D. Calibrated simulation</td>
<td>Savings are determined through simulation of the energy use of the whole facility or a sub-facility</td>
</tr>
</tbody>
</table>

IPMVP stipulates four alternative methods based on the range and type of parameters which need verification, and these methods are summarized in Table 2. For the Energy Star Appliance program, Method B was viewed as appropriate.

For this project, field measurement consisted of fifteen minute interval energy use data for refrigerators and clothes washers, as well as for other major end uses not reported on in this study. Data was collected for forty residential dwellings for a period of thirteen months. The sample of dwellings was randomly chosen from a frame of households which had participated in the Residential End Use Survey and agreed to participate in further end use research. Most electric and gas utilities use relatively short periods of field data collection, often just two weeks to four weeks, but because energy use in this jurisdiction exhibits significant seasonality it was viewed by the evaluation team as preferable to collect information for thirteen months so that annual load shape profiles could be readily established.

Five visits were undertaken at each of the forty residential dwellings in the sample. During the initial visit: (1) a survey of customer energy use and behaviours was undertaken; (2) a comprehensive inventory of energy using appliances was undertaken; and (3) meters were installed. Second, third and fourth visits were undertaken at approximately three-month intervals to download data and ensure that meters and data loggers were working appropriately. During the fifth visit, (1) the last three months of data was downloaded; (2) exit surveys were administered; and (3) the meters were removed. The metered data was cleaned and various statistics were estimated, including average energy and peak demand data. Since the utility is located in a space heating climate, the peak period was defined as 16:00 hours to 20:00 hours on an average winter week-day.

#### 2.3 Program Energy and Peak Demand Savings

Program energy savings were estimated using algorithm (13), where $\Delta GWh_i$ is monthly program energy savings for appliance $i$; $\text{Total Units}_i$ is the total number of program induced appliances per month; $\text{Share}_i$ is the share of appliance $i$ in the total; and $\text{Unit Energy}_i$ is annual unit energy savings for appliance $i$.

$$\Delta GWh_i = \text{Total Units}_i \cdot \text{Share}_i \cdot \text{Unit Energy}_i$$ \hspace{1cm} (13)$$

Program demand savings were estimated using algorithm (15), where $\Delta MW_i$ is peak demand program energy savings for appliance $i$; $\text{Total Units}_i$ is the total number of program induced appliances per month; $\text{Share}_i$ is the share of appliance $i$ in the total; and $\text{Unit Peak Demand}_i$ is peak demand savings for appliance $i$.

$$\Delta MW_i = \text{Total Units}_i \cdot \text{Share}_i \cdot \text{Unit Peak Demand}_i$$ \hspace{1cm} (14)$$
2.4 Appliance Sales Impact Model

The following monthly econometric model (16) for the eighty-eight months from January 2003 to March 2010 was used to estimate the impact of the program on monthly appliance shipments:

\[ \text{Ship}_m = \alpha + \beta \text{Perm}_m + \gamma \text{Wage}_m + \delta \text{ESARP}_m + \theta \text{Q2}_m + \lambda \text{Q3}_m + \eta \text{Q4}_m + \epsilon_m \]  

(15)

where the variables (and their sources) are as follows: Ship is shipments of Energy Star qualifying refrigerators and clothes washers (obtained from the from the Canadian Appliance Manufacturers Association), Perm is residential building permits (obtained from BC Statistics); wage is the average wage rate (obtained from BC Statistics); ESARP is a dummy variable for presence of the Energy Star Appliance Rebate program (obtained from the program records); Q2, Q3 and Q4 are quarterly dummy variables; \( \epsilon \) is an error term; and the subscript \( m \) indexes the months.

3. Results

3.1 Energy Star Appliance Sales

Time-series regression models were used to estimate the impact of the Energy Star Appliance program on appliance sales. To explore the impact of the level of aggregation across appliance types on estimated program impact, three time-series regression models were estimated: (1) a combined sales model; (2) a refrigerator sales model and (3) a clothes washer sales model.

Each of the next three tables follows the same format. The first column lists the variables in the model. The second column shows the values of the estimated regression coefficients as well as the values of the adjusted R-squared, the Durbin-Watson statistic and the F statistic. The third column shows the values of the estimated first-order auto-correlation corresponding to the Durbin-Watson statistic. The fourth column shows the significance of the t-value for the regression coefficients as well as the significance of the F statistic.

Table 3 provides the results for the model of the combined sales of Energy Star qualifying refrigerators and clothes washers. The regression says that the presence of the Energy Star Appliance program increases sales of Energy Star qualifying refrigerators and clothes washers by 367 units per month, and that an increase in the wage rate or an increase in housing starts increases sales of Energy Star qualifying refrigerators. The regression diagnostics are all adequate: the adjusted R-squared value is 0.52, auto-correlation is not a major issue, and the regression is significant at the 0.01% level based on the F-test.

Table 4 provides the results for the model of the sales of Energy Star qualifying refrigerators. The regression says that the presence of the Energy Star Appliance program increases sales of Energy Star qualifying refrigerators by 1989 units per month, and that an increase in the wage rate or an increase in housing starts increases sales of Energy Star qualifying refrigerators. The regression diagnostics are all adequate: the adjusted R-squared value is 0.76, auto-correlation is not a major issue, and the regression is significant at the 0.01% level based on the F-test.

Table 5 provides the results for the model of the combined sales of Energy Star qualifying clothes washers. The regression says that the presence of the Energy Star Appliance program increases sales of Energy Star qualifying clothes washers by 367 units per month, and that an increase in the wage rate or an increase in housing starts increases sales of Energy Star qualifying refrigerators and clothes washers. The regression diagnostics are all adequate: the adjusted R-squared value is 0.52, auto-correlation is not a major issue, and the regression is significant at the 0.01% level based on the F-test.
Table 5

| Variable                  | Coefficient estimate | Standard error | t value | Pr > |t| |
|---------------------------|----------------------|----------------|---------|------|---|
| Constant                  | -17758               | 6261           | -2.84   | 0.0069 | |
| Program                   | 367                  | 539            | 0.68    | 0.50  | |
| Wage rate                 | 25.6                 | 8.4            | 3.05    | 0.0039 | |
| Building permits          | 0.0029               | 0.00079        | 3.63    | 0.0007 | |
| Quarter 2                 | 477                  | 322            | 1.46    | 0.15  | |
| Quarter 3                 | 646                  | 323            | 2.00    | 0.051 | |
| Quarter 4                 | 783                  | 328            | 2.39    | 0.021 | |
| Adjusted R-squared        | 0.52                 | -              | -       | -     | |
| Durbin-Watson             | 1.30                 | 0.34           | -       | -     | |
| F                         | 10.03                | -              | -       | <.0001| |

After reviewing the regression results for the three models, it was agreed that it was appropriate to use the results of the combined model for further analysis, because of the superior statistical properties of Model 1 compared to Models 2 and 3. For Model 1, total program influenced sales of 2355 units was disaggregated between refrigerators and clothes washers based on their shares of program incented units.

3.2 Energy Savings

Table 6 provides the estimated energy savings for Energy Star refrigerators and clothes washers. Energy savings for each appliance is the product of total units per month (from regression Model 1), the specific appliance share of the total (from program data on incentive shares), number of months of program operations examined (from the program data) and unit energy savings (from the measurement and verification field work). Over the twenty-six months evaluated, the program resulted in purchase of an additional 26,778 Energy Star refrigerators which saved 0.51 MW of electricity per year and purchase of an additional 32,452 Energy Star clothes washers which saved 1.91 MW of electricity at system peak.

Table 6

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<tr>
<th>Component</th>
<th>Refrigerators</th>
<th>Clothes washers</th>
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<tbody>
<tr>
<td>Total units per month</td>
<td>2355</td>
<td>2366</td>
</tr>
<tr>
<td>Appliance share of total</td>
<td>0.470</td>
<td>0.530</td>
</tr>
<tr>
<td>Number of months</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Additional program units</td>
<td>28778</td>
<td>32452</td>
</tr>
<tr>
<td>Energy savings per unit (kWh/y)</td>
<td>55.9</td>
<td>188.0</td>
</tr>
<tr>
<td>Total energy savings (GWh/y)</td>
<td>1.6</td>
<td>6.1</td>
</tr>
</tbody>
</table>

3.3 Peak Demand Savings

Table 7 provides the estimated peak demand savings for Energy Star refrigerators and clothes washers. Peak demand savings for each appliance is the product of total units per month (from regression Model 1), the specific appliance share of the total (from program data on incentive shares), number of months of program operations examined (from the program data) and unit peak demand savings (from the measurement and verification field work). Over the twenty-six months evaluated, the program resulted in purchase of an additional 26,778 Energy Star refrigerators which saved 0.51 MW of electricity per year and purchase of an additional 32,452 Energy Star clothes washers which saved 1.91 MW of electricity at system peak.

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<td>26</td>
</tr>
<tr>
<td>Peak demand savings per unit (W)</td>
<td>17.7</td>
<td>58.6</td>
</tr>
<tr>
<td>Total peak demand savings (MW)</td>
<td>0.51</td>
<td>1.91</td>
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4. Conclusion

Many observers believe that anthropogenic greenhouse gas emissions are the major cause of medium-term climate change. In North America, the energy sector is responsible for two-thirds of greenhouse gas emissions, and increasing end use energy efficiency is one of the main policy instruments to reduce them.

The purpose of the voluntary Energy Star program is to identify and promote energy efficient products with the goal of reducing energy consumption and related carbon dioxide emissions. This paper provides the results of a detailed evaluation of BC Hydro’s Energy Star appliance program for its first twenty-six months of operation, using data from engineering field studies and time-series modelling.

The paper has three main findings. First, the program resulted in the purchase of an additional 26,778 Energy Star refrigerators and an additional 32,452 Energy Star clothes washers. Second, the additional Energy Star refrigerators saved 1.6 GWh of electricity per year and the additional Energy Star clothes washers saved 6.1 GWh of electricity per year. Third, the additional Energy Star refrigerators reduced peak demand by 0.51 MW and the additional Energy Star clothes washers reduced peak demand by 1.91 MW.

Acknowledgement

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References