Market penetration modeling of high energy efficiency appliances in the residential sector

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Abstract

The aim of this research is to model the market penetration of energy efficient appliances in the residential sector. The analysis focuses on six major appliances – refrigerators, freezers, clothes washers, clothes dryers, and ranges – to forecast their market penetration and market share during the years 2012-2050. Models were developed for each category using 22 years of historical data related to population, household income, immigration, and appliance price. These variables were selected based on the statistical tests of twelve macroeconomic variables. The market shares of high efficiency appliances were analyzed based on the related capital costs, operating costs, lifetime, and incentive. The results show that in Alberta the market penetration growth rate of dishwashers is higher than that of all other appliances, with a projected 30.52% increase between 2012 and 2050. The modelling results also indicate that the average annual energy consumption by refrigerators will decrease from 560.9 kWh in 2012 to 460.8 kWh in 2050, and this decrease indicates an annual energy efficiency improvement of 0.47%. In addition, the effect of an incentive on adopting high energy efficiency appliances and ultimately on energy efficiency improvement in Alberta is more effective for dishwashers and clothes washers.

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Nomenclature

a	Constant coefficient in each developed model and varies for variables
AAE	Absolute average error
Adjusted R^2	*Adjusted R-Squared* is useful to analyze the fitting degree when the number of actual data is relatively high
APH	appliances per household
app_cpi	Appliance CPI
b	Constant coefficient in each developed model and varies for variables
c	Constant coefficient in each developed model and varies for variables
CAD	Canadian dollar
CC_i	The capital cost of item i
CPI	Consumer price index
d	Constant coefficient in each developed model and varies for variables
elec_cpi	Electricity CPI
ε	The residual value in each point.
F-statistic	Function statistic test
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoule, equal to 10^9 J
Income_hh	Household income
kWh	kiloWatt-hour
nat_mig	National migration
NEMS	National Energy Modeling System
NRCan	Natural Resources Canada
OC_i	The operating cost of item i
popu	Population
Prob. a	Probability or "the *p-value" of coefficient "a"*
Prob. b	Probability or "the *p-value" of coefficient "b"*

Prob. c	Probability or "the *p-value" of coefficient "c"*
Prob. d	Probability or "the *p-value" of coefficient "d"*
Prob. e	Probability or "the *p-value" of coefficient "e"*
Prob. F statistic	Probability of function statistic test
R^2	*R-squared which* analyzes the fitting degree of actual data by the developed model
StatCan	Statistics Canada
U.S.	United States of America
UEC	Unit energy consumption
unempl-rate	Unemployment rate
urban	Urbanization
$Weight_i$	The weight of item i
x	The macroeconomic variable effective in market penetration modeling
x1	Variable used in market penetration modeling
x2	Variable used in market penetration modeling
x3	Variable used in market penetration modeling

1. Introduction

The improvement of energy efficiency in the energy demand sector has key impacts on energy consumption and GHG mitigation [1]. Forecasting the overall energy efficiency for the energy sector is the function of a series of variables including technical and economical parameters affecting the market penetration of high energy efficiency technologies [2]. Modeling the penetration of high energy efficiency equipment in the energy demand sectors is critical not only to analyze the energy demand of future years but also to manage the policies formulated by public or private organizations to achieve energy or environmental targets [3].

Energy intensity in the residential sector of Alberta, a province in Canada, was 148.52 GJ per household in 2011, 38% more than the national average of 107.75 GJ [4]. The province of Alberta has the highest per household energy consumption among the provinces [5]. Energy intensity by appliance in Alberta was 17.01 GJ per household in 2011, which put this province

second in the country after Manitoba [5] and was 25.2% higher than the average of the other provinces and territories in energy consumption by appliance. The total stocks of appliances per household in Alberta were 21.7, which was 2.25% lower than Canada's average [6].

In Alberta, 49% of refrigerators have the ENERGY STAR® label, which is a consumer icon in the Canadian marketplace [7]. The ENERGY STAR product label identifies products that are qualified as high efficiency [8]. These products have higher energy efficiency than regular ones and are considered energy efficient [9]. Under an agreement with the U.S. Environmental Protection Agency (EPA), Natural Resources Canada (NRCan) administers and monitors the ENERGY STAR name and symbol in Canada. It should be mentioned that, as of the time of this study, there are no ENERGY STAR standards formulated for ranges [10]. The history of specification differences between ENERGY STAR and regular appliances shows that ENERGY STAR appliances have 20-30% more energy efficiency than regular ones [10]. The shares of ENERGY STAR use for dishwashers, freezers, and clothes washers are 42%, 23%, and 50%, respectively, all of which are higher than Canada's average values (37%, 22%, and 48%, respectively) [11].

Market penetration and market share models could provide insights into the penetration rates of efficient household appliances based on basic parameters and historical data [12]. Market penetration refers to the number of people who buy a specific product in a period of time, and market share is the percentage of the market accounted for by a specific product [13]. There is limited research on the assessment of market penetration through comprehensive models. A few studies on the impact of some methods of improving average energy efficiency have been done, for instance on labeling, incentives for purchasing high efficiency appliances, and pricing policy [14-17]. Market penetration modeling based on econometrics and time series analysis combined with cost models has not been done for high energy efficiency appliances. Hence, the main objective of this paper is to assess the market penetration and market shares of energy

efficient appliances by developing a comprehensive framework based on econometrics and time series analyses combined with cost models.

2. Method

The method used in this study was to develop data-intensive models to estimate of the market penetration of residential sector appliances over a time period. The developed models used a number of macroeconomic and technical parameters. Figure 1 shows the steps involved in developing the framework. The model is described in more detail in the sections that follow.

Statistical data and time series information of appliances for Alberta were extracted from publically available resources including NRCan [5] and StatCan [11]. Some of the key parameters considered are: population, household income [6], electrification, urbanization, consumer price index (CPI) [6], international and inter-provincial immigration to Alberta [18], unemployment rate [19], and people's awareness of the benefits of high energy efficiency appliances [20]. Other parameters, such as look, color, and style, which affect the adoption of appliances, were not considered in this study.

2.1. Market penetration modeling

There are different means of modeling the market penetration of energy technologies. These include subjective methods-based models, cost models, time series models, and econometrics diffusion models [21]. No one approach can be used for all circumstances. Models that are more complex make more reliable results, but they usually need more data [22]. Subjective estimation methods are used if there is little or no historical data available for related technology [13]. Market surveys are recommended if available categorized data is not enough. In case of those

technologies which costs and economic factors are available, cost estimation models are suggested [23]. For those technologies with two types of adopters (innovators and imitators), diffusion models could be a good option [24]. For market penetration of new technologies which are related to a set of other factors including economic variables, econometric models could have reliable results but they need statistical analysis [25]. Due to the availability of appliance data in Alberta's residential sector, econometric diffusion models were selected for market penetration forecasting.

In econometric diffusion models, all variables affecting market penetration are analyzed. Average values of the related variables such as price of the appliance or energy consumption by the appliance were used.

To analyze the variables' effects on the market penetration of different appliances, individual variable probability tests were done using the least square method and based on Pearson's correlation (Equation 1) [26]:

$$\square\square(\square\square\square) = \square + \square \times \square\square(\square) \quad (1)$$

where

APH is appliances per household;

$\square$ is the macroeconomic variable effective in market penetration modeling and includes household income, appliance price, and electricity price; and

$\square$ and $\square$ are constant coefficients in each developed model and vary for different variables.

After selecting appropriate parameters, econometric diffusion functions for market penetration were developed for each appliance. The general structure of the model is as follows [27]:

$$\square\square(\square\square\square) = \square + \square \times \square\square(\square_{\boldsymbol{1}}) + \square \times \square\square(\square_{\boldsymbol{2}}) + \square \times \square\square(\square_{\boldsymbol{3}}) + \cdots \quad (2)$$

where

$\square_1$, $\square_2$, and $\square_3$ are variables that will be used in market penetration modeling; and

$\square$, $\square$, $\square$, and $\square$ are constant coefficients in each developed model.

This model was developed based on the Cobb-Douglas production function, which studies relationships between economic inputs and outputs with technology changes with time [28]. The general concept behind this model has been used widely in different fields of science and engineering and in estimating and analyzing the demand level for a sector, country or a region [29]. The production model provides analyses from the perspective of system-level studies based on a conceptual relation between dependent and independent variables [30]. The developed mathematical equations were verified through statistical tests and were used in market share modeling and energy efficiency improvement analysis [31]. In addition, a sensitivity analysis was done to determine the effects of changes in each independent variable on the mathematical equation function [32].

2.2. Market share modeling

As shown in Figure 1, once the models generated appliance market penetration per household, the market shares adopted by different technologies were calculated. The concept of market share modeling is based on logit models, which have been used in some other studies [33].

The process for a market share analysis is applied to both new equipment purchases and decisions to replace existing appliances [22]. Competing technologies for a particular appliance

are weighted based on capital and operating costs [34]. Market share for each appliance is calculated using Equations 3 and 4 [35]:

$$\text{Market share}_i = \frac{\text{Weight}_i}{\sum \text{Weight}_i} \quad (3)$$

$$\text{Weight}_i = i^{(a \times CC_i) + (b \times OC_i)} \quad (4)$$

where

Weight$_i$ is the weight of item i;

CC$_i$ is the capital cost of item i;

OC$_i$ is the operating cost of item i; and

a and *b* are coefficients based on historical data and discount rates, different for each technology.

The lifetime of each appliance and stocks per household in different years are used to calculate new adoption rates for each option available for different appliances. A similar approach was used in end-use technology choices in the National Energy Modeling System (NEMS) [35]. NEMS's model is the most influential energy model in the United States and has been used by the U.S. Energy Information Administration to develop long-term forecast of energy consumption in the country [35].

Developing market penetration and market share models for each appliance helps formulate different scenarios based on macroeconomics variables. In addition, it is possible to analyze the effects of fuel pricing policies and incentives on the adoption of high efficiency appliances and unit energy use.

Each appliance was divided into two major categories, high energy efficiency and regular energy efficiency. Capital costs and operating costs of each appliance were used in modeling the market share, and the effects of incentives on the purchase of high efficient appliances were analyzed.

It has been assumed that there is no limit in the supply of appliances to the Alberta market. In terms of the supply of electricity from the province's grid network, as shown in Figure 2, electricity is available in almost all parts of the province. Thus, it is assumed that there is no limit in the supply of electricity for residential sector appliances.

3. Model statistical tests and validation

The analysis of different variables affecting the market penetration of appliances is based on Equation 1. This equation was used for each major appliance (refrigerators, freezers, dishwashers, clothes washers, clothes dryers, and ranges). In addition, this study attempted to include all effective variables. The results of probability tests, along with modeling and other statistical tests for refrigerators are given in Table 1.

The fitting parameters in Equation 1 were adjusted using the statistical computation software "*Eviews 8 SV*" [36]. The conventional ordinary least squares (OLS) method was implemented, and statistical tests were used to analyze different aspects of developed model.

Prob. Probability is a statistical test that analyzes the effectiveness of individual variables in modeling that have been used in modeling. Probability is also known as "the *p-value"* or "the *marginal significance level."* If the value of this test is lower than 0.05, it could be evidence that the related coefficient has a significant role in modeling [36]. In Table 1, the probability values for all used variables in modeling are lower than 0.05 except in the case of refrigerator

expenditure. Therefore, most of the selected variables in Table 1 can be effective in market penetration model development for refrigerators.

R-squared (R^2) analyzes the fitting degree of actual data by the developed model. This parameter should be equal to 1 if the developed model fits the actual data [36]. The values of "R-squared" for each variable have been shown in Table 1.

Adj. R-squared (Adjusted R^2) is useful to analyze the fitting degree when the number of actual data is relatively high. In other words, *Adj. R-squared* is helpful to avoid undesired *R-squared* increasing and shows the real situation of fitting. The value of *Adj. R-squared* is always lower than or equal to the *R-squared value*, and, for inappropriate fitting situations, could be negative [36]. The values of "R-squared" and "Adj. R-squared" in Table 1 show that "population," "household income," and "appliance CPI" are more effective than other variables in developing market penetration models for refrigerators (Table 1).

The *F-statistic* test assumes that all of the coefficients in the developed model (excluding the constant, or intercept) are equal to zero. So if the value of "Prob. F statistic" is close to 1, it shows that the developed structure for the model is not acceptable.

This statistic shows the distribution of the F-statistic. The acceptable level for the P-value of the F-statistic is 0.05, which shows that the maximum acceptable probability of this hypothesis is 5% [36]. As shown in Table 1, the values of this statistic test for all variables are close to zero, so all of these variables could have a role in model development.

The Durbin-Watson (DW) statistic test detects the serial correlation among the residuals. The residual value is the difference between actual data and modeled results at each point. This statistics were calculated with Equation 5 [37].

(5)

ε is the residual value in each point. The values of DWs lower than 1.0 are evidence of positive serial correlation [36].

Different statistical tests such as “Prob.” and “R-squared” work as filters to have appropriate model development and to achieve reliable results. Based on the statistical test results shown in Table 1, it has been observed that “population,” “household income,” “floor space per household,” and “inter-provincial immigration” have a direct effect on market penetration model development. Because not only the values of “Prob. A” are “Prob. B” are equal to zero and Adj. R-squared is more than 0.80, but also conceptually changes in these variables affect appliance adoption. “Appliance CPI,” “electricity CPI,” and “urbanization,” along with “unemployment” and “national immigration,” have lower values of “Adj. R-squared”. In addition, they have indirect role in market penetration model development. It should be mentioned that the impact of both “national” and “inter-provincial immigration” has been considered in total population and also in household number. In other words, increased national and inter-provincial immigration leads to both higher total population and higher total household number.

Analyzing the available data for “appliance expenditure” and “electricity expenditure” in the residential sector shows that these two variables have arisen from the number of appliances per household. These variables are categorized as dependent variables and so will not be used as independent variables in modeling.

Based on the above analyses, effective variables for each appliance were selected and market penetration models were developed. Validation results of the developed market penetration models are shown in Figure 3.

An analysis of the graphs in Figure 3 shows that the developed mathematical models appropriately follow the actual data. As with other appliances, the figures in the developed models for these appliances follow the changes in actual data smoothly. Error calculation was done to test the models by using the percentages of absolute average error (AAE) for all the appliances.

Table 2 shows that the modeling results follow actual data within a good level. The percentage of average absolute error for the modeling is less than 3% for all appliances.

4. Results and discussion

In this section, results obtained from different steps of the modeling are presented and discussed. The results included the market penetration of appliances, the market share of high energy efficiency appliances, and the impact of incentives on market energy efficiency improvement.

4.1. Appliances' market penetration and share modeling

Econometrics mathematical functions were developed based on twenty-two years of historical data (1990-2011) by using least-square analysis for each appliance, different variables were analyzed, and the selected mathematical structure passed all the statistical tests. In addition, the developed models passed the market penetration concept. The econometric diffusion modeling results for the penetration of residential appliances in Alberta are given in Table 3. Table 4 presents the statistical test results of the developed models for major residential appliances.

Analyzing the results shows that the effects of increases in “population” and “household income” on the market penetration of all appliances are positive. Also, increasing electricity price has a negative effect on market penetration. The table also shows the comparison between the effects of electricity price and appliance price on market penetration. An evaluation of the equations in Table 3 shows that the impact of changes in appliance CPI is much greater than the impact of electricity CPI on appliance penetration. Therefore, formulating and implementing appliance price policies can have a high impact on energy efficiency improvement.

The values of R-squared and adjusted R-squared are close enough to the number one. In addition, they are at an appropriate level for a good fit between actual data and modeled results. The Prob. F-statistic of is almost zero for all models, which indicates that the structure of all models is acceptable for fitting the actual data. The values of probabilities for all coefficients are lower than 0.1, but most of them are lower than 0.05. Therefore, statistical test results indicate that the developed penetration models pass statistical tests properly.

The values of DWs presented in Table 4 show that the probability of serial correlation is very low in the developed models. In other words, adding another variable to cover the residual values of fitting in not required. The model’s results for appliance penetration rate per household in the residential sector are shown in Figure 4.

An analysis of Figure 4 shows that the market penetration of refrigerators is higher than that of other appliances. The stocks of refrigerators per household are anticipated to increase from 1.28 in 2012 to 1.314 and 1.328 in 2030 and 2050, respectively.

An assessment of the modelling results shows that the market penetration rate of stand-alone freezers will decrease between 2012 and 2050. Freezer stock per household will decline from 0.634 in 2012 to 0.556 and 0.515 in 2030 and 2050, respectively. One of the reasons for this

decrease is the improved small freezer section in refrigerators (top-mounted, side-mounted, or bottom-mounted).

The increase in the market penetration rate of dishwashers is higher than for all other major appliances. The stock of dishwashers per household is expected to increase from 0.761 in 2012 to 0.865 and 0.960 in 2030 and 2050, respectively. Therefore, it is recommended that pricing policies be formulated and implemented on higher energy efficiency dishwashers because of their projected high growth rate in the market.

The increase in the market penetration rate of clothes washers and clothes dryers is nearly parallel. The stock of clothes washers and clothes dryers per household is expected to rise from 0.893 and 0.979 in 2012 to 0.960 and 1.0 in 2050, respectively. In other words, there is likely to be a huge market for clothes washers and clothes dryers by the end of the study period, and, as with dishwashers, formulating and implementing pricing policies to encourage households to adopt high energy efficient brands of these two appliances will help improve overall energy efficiency.

The total appliance penetration growth rate during the study period is shown in Table 5. Analyzing the developed model and historical data for ranges do not show a big change in market penetration growth rate and is expected to remain at one per household. Therefore, market penetration in terms of changes in the number of ranges per household equals zero. Dishwashers and freezers have the highest and lowest market penetration growth rates from 2012 to 2050, 0.803% and -0.494%, respectively.

In general, the efficiency is the ratio between the output and input energy. The output energy can be in different forms, but in energy efficiency calculation, the desired form of energy is considered as output energy. According to the second law of thermodynamic theory, the

maximum achievable efficiency is not more than the energy efficiency of Carnot process. Technical and thermodynamic specifications of each appliance have been considered in this section [38].

As shown in Figure 5, different appliances have different adoption rates. Market share models show that people are interested in adopting high efficiency appliances and the interest is higher for dishwashers and freezers than for other appliances. In 2012, the adoption shares of high efficiency dishwashers and freezers (rather than regular ones) were 0.459 and 0.458, respectively. These shares are expected to increase to 0.799 and 0.744 in 2030 and to 0.985 and 0.970 in 2050, respectively.

The market penetration rates among high efficiency clothes washers, refrigerators, and ranges are similar. The adoption shares of high efficiency dishwashers, refrigerators, and ranges are expected to increase from 0.567, 0.588, and 0.631 in 2012 to 0.654, 0.687, and 0.718 in 2030 and 0.770, 0.841, and 0.839 in 2050, respectively. The adoption share for high efficiency clothes dryers will increase during the study period (0.595 in 2012 to 0.668 in 2050). An analysis of the results shows that dishwashers and freezers have the highest growth rates of energy efficient appliances' adoption. Although the total market of stand-alone freezers decreases over time, that limited number of freezer adopters is more willing to buy energy efficient than regular energy efficiency ones.

Appliance price is one of the factors affecting the adoption of high efficiency appliances. The rate of increase of appliance price is lower than overall rates of inflation because of high sales volumes, which result in economies of scale benefits that result in more households purchasing the appliances. The changes in the real price of appliances were considered by using the CPI in modeling.

In the modeling of market share of dishwashers and clothes washers, water consumption and water price could be important. The cost of required water for these two appliances was calculated in this study and it shows that this cost is around 2% of electricity cost. Therefore, the effect of changing the water price is negligible in market penetration and market share modeling. Moreover, people's awareness of high energy efficiency appliances in Canada increased to 80% by 2005, which is a good level. In the current study, it has been assumed that almost all adopters are aware of high efficiency appliances when they buy new ones. Providing information on high energy efficient appliances to costumers is already supported by regulations [39].

4.2. The impact of incentives on market share

Incentives are one of the parameters that have a significant impact on the adoption of high efficiency appliances. A review of the funding available for energy efficiency programs in Canada and the U.S. shows that there have been few such incentives programs in recent years [40].

Incentive can be in the form of tax credit or cheque payment for respective products and can be different in counties or region of the province. The amount of incentive for different energy end-users and appliances could be different in residential sector. It could be related to the type of energy end-users and mostly is changing from $50 to $500 in North America. As a scenario, it was assumed that CAD $300 were available as an incentive to adopt high efficiency appliances. This incentive would be paid once in the period 2015 to 2020 to each household for each major high efficiency appliance purchase. The effect of a CAN $300 incentive to adopt new high efficiency appliances during the years 2015 to 2019 is shown in Figure 6.

The impact of incentives is not the same for all appliances. This impact depends on effective variables such as the cost of the appliance and the amount of energy used by a particular

appliance. As shown in Figure 6, the effect of incentives on the adoption of high efficiency appliances is higher for dishwashers and clothes washers than for other appliances. Incentives have the least effect on the adoption of clothes dryers. It should be mentioned that average annual energy use in ranges is higher than for other appliances in Alberta's residential sector. As there is no ENERGY STAR label for residential ovens and ranges at the time of this study, formulating ENERGY STAR specifications for ranges and encouraging people to adopt high energy efficiency ranges is recommended.

Using the high efficiency appliance penetration rates based on the business-as-usual scenario and the incentive program, the average values of unit energy consumption were modeled for each appliance for the years 2012 to 2050. Business-as-usual scenario is an unchanging state of the trends of independent variables. The model's projected results are shown in Figure 7. The incremental impact of incentives on UEC improvement rather than business-as-usual scenario has been shown in Figure 8.

An analysis of the results shows that average annual energy consumption decreases over time for all major appliances. A similar trend can be observed in historical data. Clothes dryers and ranges consume the highest energy annually. The average annual energy consumption for clothes dryers is expected to decrease from 1013.4 kWh in 2012 to 953.9 and 885.0 kWh in 2030 and 2050, respectively. Of the six appliances considered, clothes washers consume the least energy. The average annual energy consumption for clothes washers will decrease from 306.2 kWh in 2012 to 156.9 kWh in 2050.

The incremental impact of CAD $300 on UEC improvement of appliances shows that there is higher potential of UEC improvement by implementing incentive program for dishwashers and clothes washers. The impact of canceling incentive program after 2019 has negative impacts on UEC improvement of all major appliances with higher impacts on clothes washers and

dishwashers (Table 6). An analysis of the results shows that the impact of canceling incentives is higher for clothes washers and dishwashers than other appliances.

4.3. Long-term energy efficiency improvement

High efficiency appliance adoption and technology improvement from 2012 to 2050 will have an obvious improvement on average annual energy efficiency. The results of the developed models show that average annual energy consumption by refrigerators will decrease from 560.9 kWh in 2012 to 460.8 kWh in 2050. This figure indicates an energy efficiency improvement of 0.47% per year. The energy efficiency improvement for freezers, dishwashers, clothes washers, clothes dryers, and ranges is 0.52%, 1.2%, 1.28%, 0.33%, and 0.38%, respectively.

The largest growth rate in energy efficiency improvement during the period 2012-2050 is projected to be for clothes dryers and dishwashers (48.76% and 45.46%, respectively) in the business-as-usual growth rates with incentives to purchase high efficiency appliances. The growth rate in energy efficiency improvement for all other appliances fall within close range: refrigerators, freezers, clothes dryers, and ranges will see growth in energy efficiency of 17.86%, 19.70%, 12.67%, and 14.47% in energy efficiency during the years 2012-2050. The annual growth rates in energy efficiency improvement for different appliances from 1990 to 2011 and from 2012 to 2050 are shown in Figure 9.

The improvement rate is not the same for every year of the study period. The rate of change is greater in the early years and lower in the later ones. The accumulative changes in appliance energy efficiency in different decades are shown in Figure 10. The effects of technology improvement on changes in energy efficiency are greater for almost all appliances in the first years of the study period. Clothes dryers and refrigerators have a higher potential for improving energy efficiency of the household sector in the first two decades rather than later years. These

two appliances can achieve up to 67.5% and 64.2% higher efficiency improvement than their average efficiencies in 2012.

4.4. Sensitivity analysis

A sensitivity analysis was done to see the impact of changes in values of key parameters on market penetration rates of appliances in Alberta's residential sector. The impact of changes in the main variables on penetration modeling functions is shown in Figure 11. Based on this sensitivity analysis, it was determined that the most important variable in refrigerator models is population, and a ±20% change in population can make a 2.22% change in market penetration. Changes in household income and electricity CPI result in changes of 0.234% and 0.359%, respectively.

The most important variable impacting the penetration of dishwashers is urbanization. A ±20% change in urbanization can result in a 22.70% change in the market penetration of dishwashers. Changes of ±20% in population, household income, electricity CPI, and appliance CPI can result in changes of 0.36%, 0.245%, 3.380%, and 8.737%, respectively, in the market penetration of dishwashers, all of which are considerably less than the effects of urbanization.

For freezers, the most notable variable is population: a ±20% change in population can result in an 8.030% change in market penetration. A ±20% change in household income, electricity CPI, and appliance CPI can make changes of 0.253%, 0.072%, and 3.761% in the market penetration of freezers.

Population is also the most important variable in the market penetration of both clothes washers and dryers. A ±20% change in population can result in a 2.86% and 1.32% change in market penetration. Population and urbanization have the largest effect on ranges. A ±20% change in population and urbanization can result in a 10.54% and an 11.41% change in the market penetration of ranges. Population, urbanization, immigration, and appliance CPI have a greater

effect on the market penetration of major appliances than do other factors. Changing household income and electricity price in the models showed little change in the market penetration of appliances.

The price of electricity is not high in Alberta. Having smart meters for electricity in the residential sector could help encourage people to control electricity use. Higher rates for mid-peak and peak hours as well as different rates for high consumption could help convince people to purchase high efficiency appliances that lead to higher average efficiency in the appliance subsector of the province. Developing and implementing electricity pricing policies for future years can be an important way to encourage residential sector market penetration of high efficient appliances, which in turn can improve average energy efficiency. In addition, formulating incentives for purchasing brand new appliances could be very effective in increasing energy efficiency.

Considering the impact of incentives on UEC improvement and GHG mitigation shows that some appliances have higher impacts on energy cost saving and GHG mitigation. After implementing CAD $300 incentive program from 2015 to 2019, it is possible to improve the UEC of dishwashers and clothes washers by 2019 by 2.84% and 2.76%, respectively, which is more than other major appliances.

The potential market of stand-alone freezers is decreasing in the province but the impact of incentives on their UEC improvement is relatively high. It means that freezers would not be the most important appliance in the future of Alberta residential market, but formulating incentives by government could encourage people to adopt efficient stand-alone freezers.

A comparison of our analysis with another similar investigation on market penetration of appliances shows that using different macroeconomic parameters in modeling helps create results that are more reliable. McNeil and Letschert developed penetration models based on

electrification and urbanization [41]. Although they did not use price as a parameter in modeling, the authors concluded that appliance price is the most significant determinant of appliance diffusion rates. In our research, appliance price and other effective market penetration parameters were used in modeling, and their impacts on energy efficiency improvement were analyzed and explained in terms of capital cost of higher energy efficiency appliances. A comparison of our results with McNeil's on refrigerators shows that appliances per household increase with average household annual income, electrification, and urbanization in both studies. Using prices in modeling let us not only analyze the effects of changes in price on market penetration of appliances but also achieve higher levels of fitting in modeling, from 66% in McNeil's model to 93% in our model for clothes washers. Therefore, it is recommended that electricity and appliance prices be used in market penetration modeling.

5. Conclusions

This research demonstrates the results of market penetration modeling of high energy efficient appliances in Alberta's residential sector for the years 2012-2050. The models were implemented in an observational combined method based on considerations of energy system parameters, econometric diffusion models, and market share functions.

Despite the fact that the price of electricity is not high in Alberta, an increase in average electricity price could improve the market penetration of high efficiency appliances in the residential sector. However, in Alberta, government incentives to encourage people to buy higher energy efficient technologies are more effective than electricity pricing policies. The effects of technology improvement on energy efficiency are greater for almost all appliances in the first years of the study period. Clothes dryers and refrigerators have a higher potential for improving household sector energy efficiency and can achieve up to 67.5% and 64.2% greater efficiency by 2050 than their average efficiencies in 2012. A comparison of our investigation with earlier studies shows that using electricity and appliance prices in modeling helps achieve

results that are more reliable. Using prices in our research helped achieve higher level of accuracy in modeling – up to 93% in our developed model for clothes washers. Finally, this study developed an approach to model the market penetration of high efficient appliances and the impacts of changes of macroeconomic parameters, appliance price, electricity price, and incentives on average energy efficiency improvement for major residential sector appliances thein other provinces or countries.

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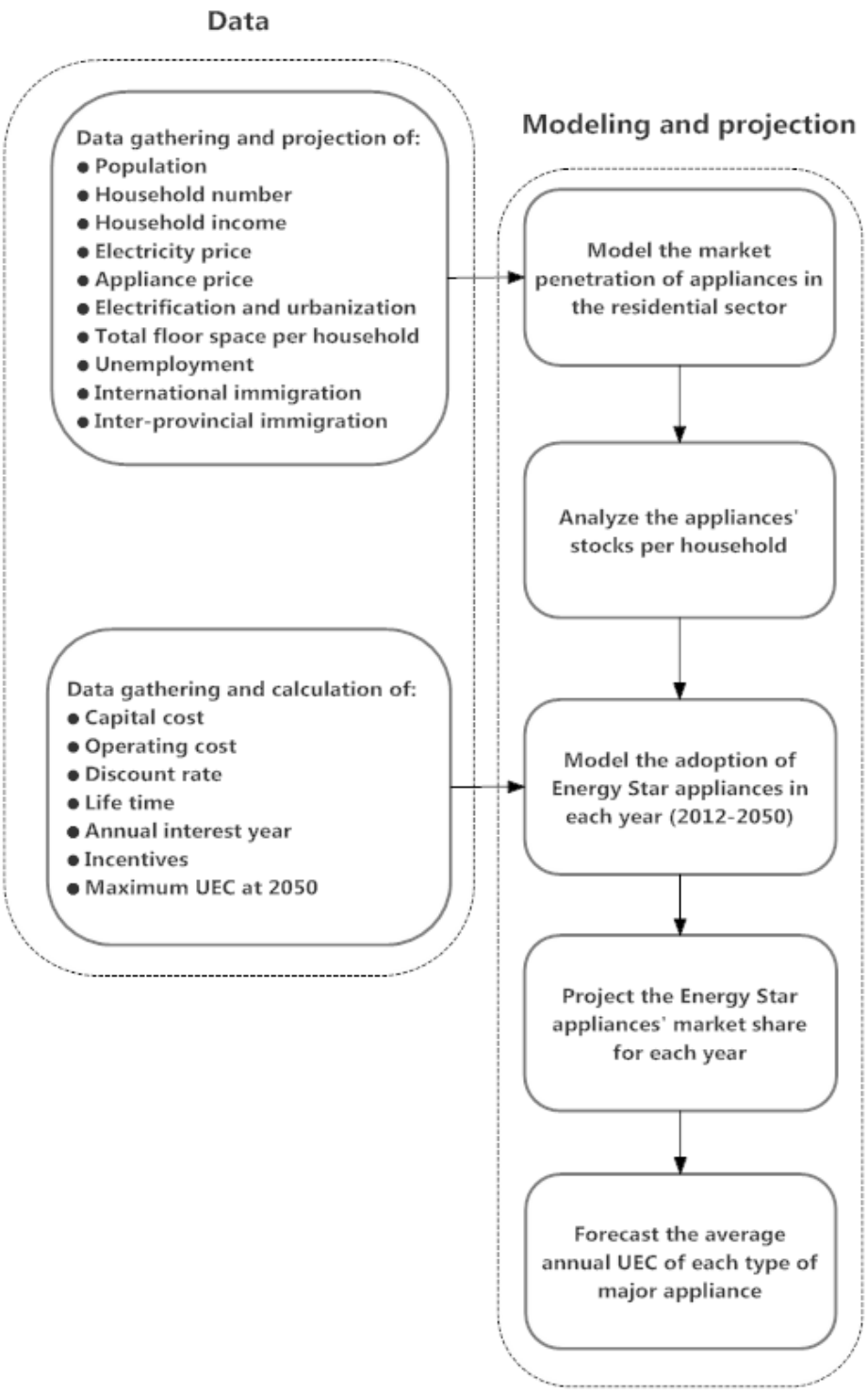

Figure 1: The method used in this study

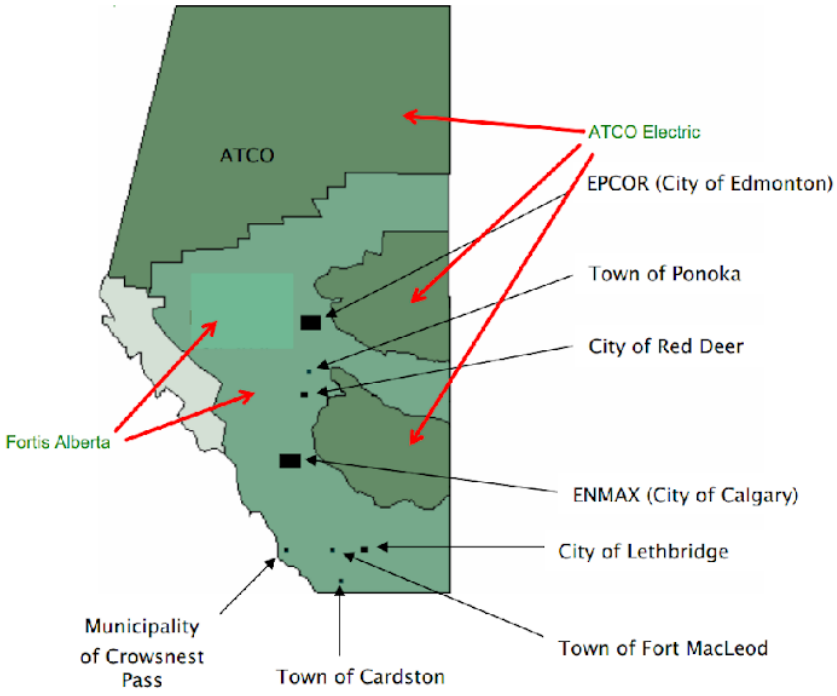

Figure 2: Alberta's electric distribution system's owners. Copyright obtained through personal communication with Gordon Howell [38]

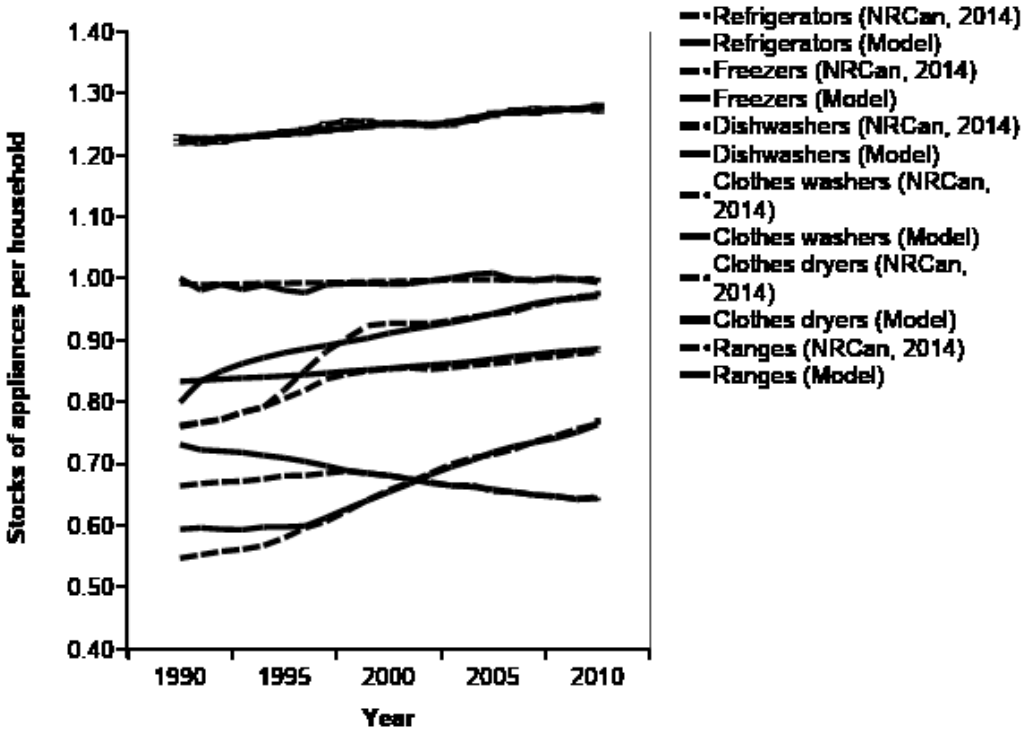

Figure 3: Validation results for market penetration modeling of appliances (1990-2012)

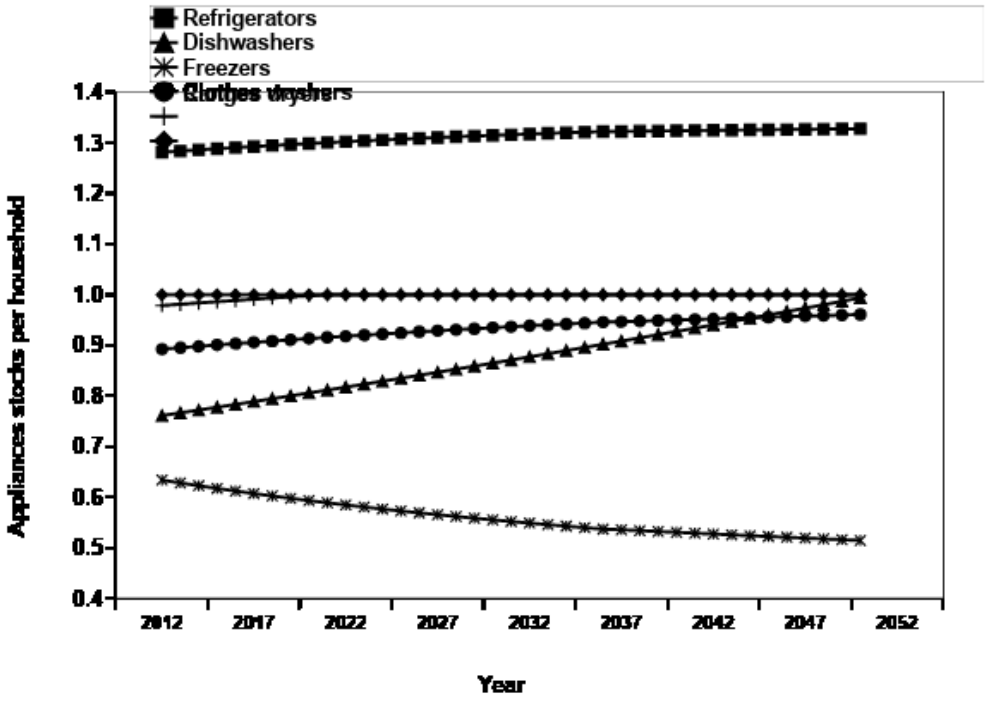

Figure 4: Projected market penetration of major appliances per household in Alberta's residential sector (2012-2050)

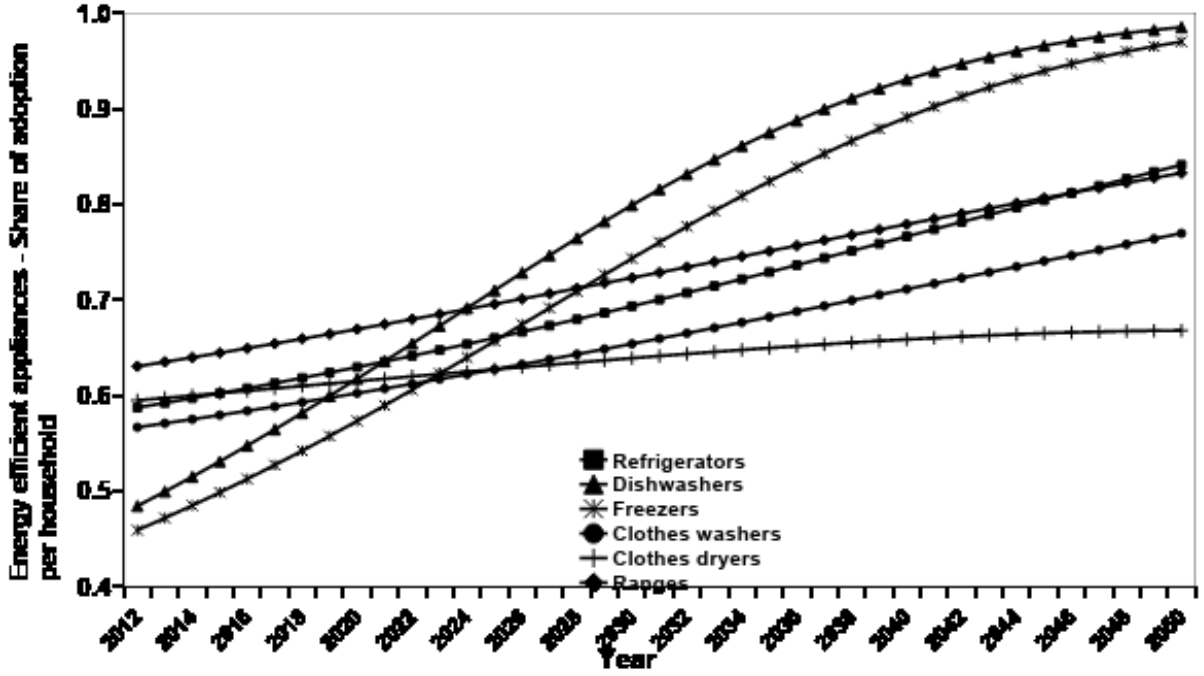

Figure 5: The adoption shares of high energy efficiency appliances (2012-2050)

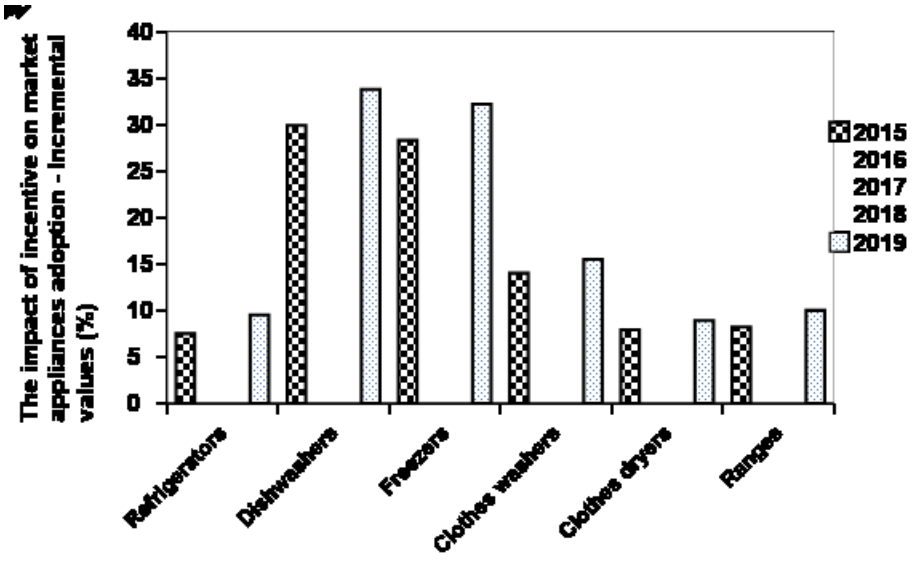

Figure 6: The impact of CAN $300 incentive in market penetration of high efficiency appliances from 2015 to 2019 vs 2014 values

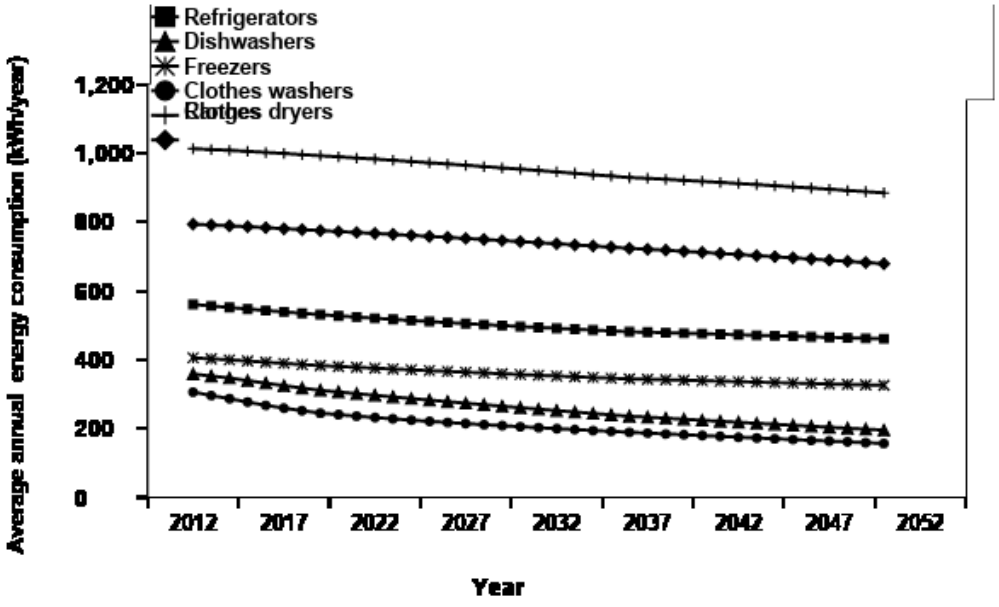

Figure 7: Average annual energy consumption of appliances based on the business-as-usual scenario with the incentive program (2012-2050)

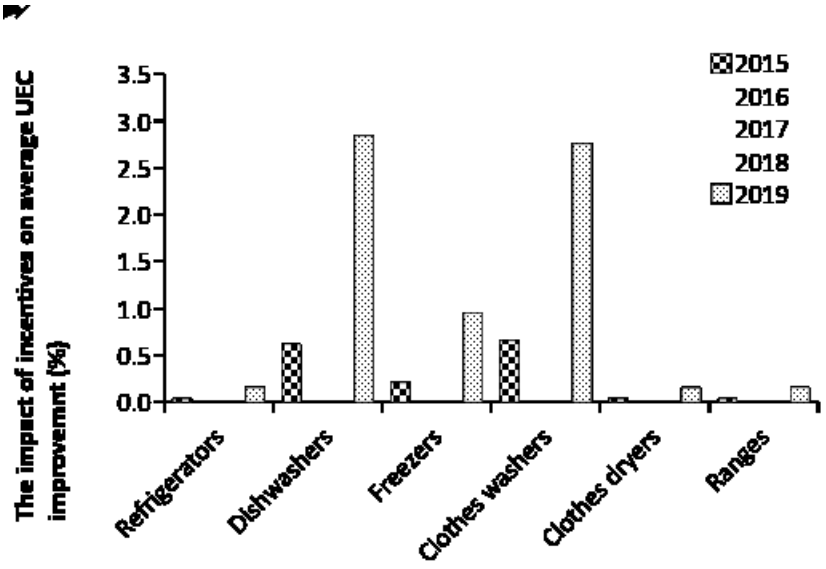

Figure 8: Incremental impact of incentives on average UEC improvement from 2015 to 2019 vs 2014

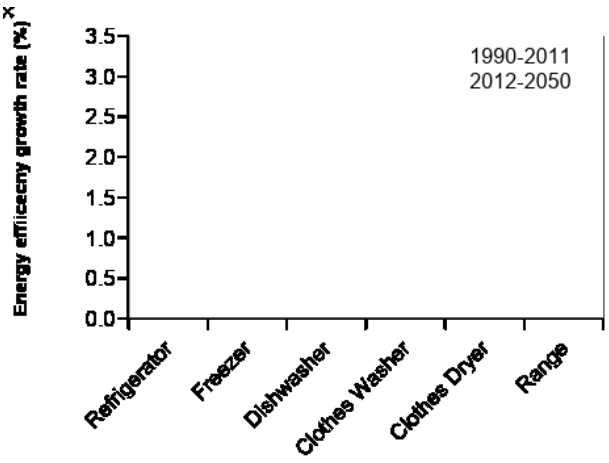

Figure 9: Annual average percentage growth rate in energy efficiency for each appliance from 1990 to 2011 and from 2012 to 2050

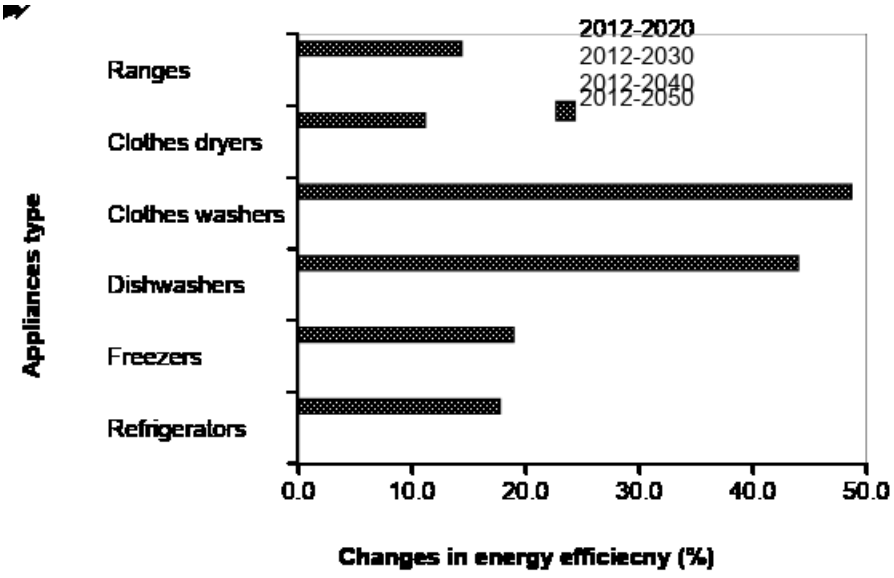

Figure 10: Accumulative changes in appliance energy efficiency by decade

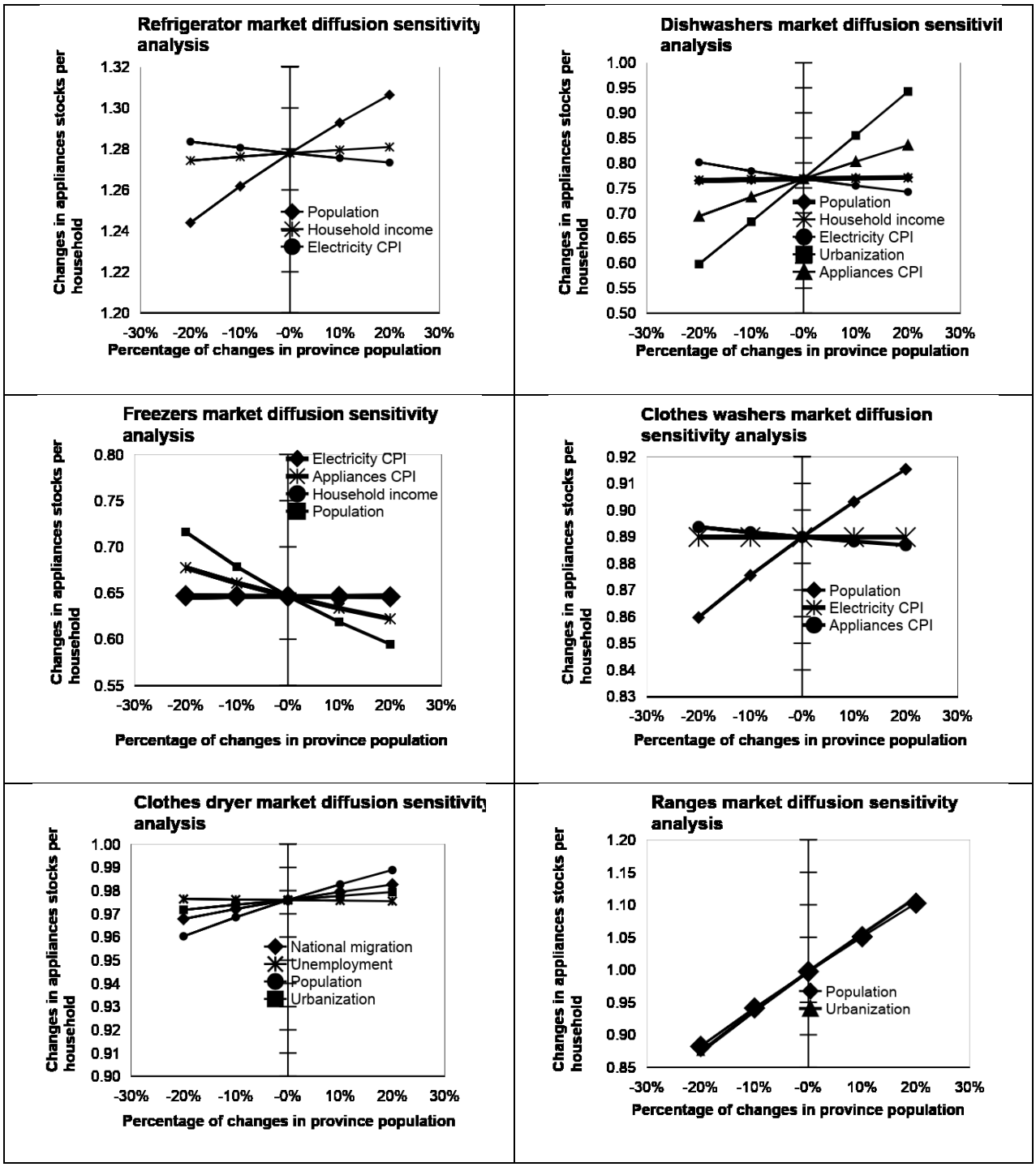

Figure 11: Sensitivity analysis results of developed penetration models

Table 1: Statistical analysis of each individual variable in the market penetration of refrigerators in Alberta's residential sector

Item	Modelling results	a	b	Prob. a	Prob. b	R-squared	Adj. R-squared	Prob. F statistic
1	Population	-0.675	0.112	0.0000	0.0000	0.908	0.903	0.000
2	Household income	-0.252	0.041	0.0000	0.0000	0.883	0.877	0.000
3	Refrigerator expenditure	0.032	0.032	0.0871	0.0000	0.856	0.849	0.000
4	Electricity expenditure	-0.797	0.147	0.0000	0.0000	0.845	0.837	0.000
5	Floor space per household	-0.753	0.202	0.0000	0.0000	0.826	0.817	0.000
6	Inter-provincial immigration	0.190	0.008	0.0000	0.0000	0.826	0.817	0.000
7	Electricity CPI	0.019	0.046	0.0418	0.0000	0.793	0.783	0.000
8	Urbanization	0.402	0.844	0.0000	0.0000	0.777	0.766	0.000
9	Unemployment rate	0.272	-0.031	0.0000	0.0000	0.573	0.552	0.000
10	Refrigerator CPI	0.989	-0.168	0.0000	0.0001	0.567	0.546	0.000
11	National immigration	-0.007	0.024	0.0496	0.0014	0.406	0.376	0.001

Table 2 : Absolute average error (%) for the appliances

Appliance	% of AAE
Refrigerators	0.162
Freezers	2.311
Dishwashers	2.043
Clothes washers	2.637
Clothes dryers	2.962
Ranges	0.499

Table 3: Econometric penetration models developed for the market penetration of appliances in Alberta's residential sector

Appliance type	Econometric penetration model	*a*	*b*	*c*	*d*	*e*	*f*	Equation number
Refrigerators	□ + □ × □□(□□□□) + □ × □□(□□□□□□_□□) + □ × □□(□□□□_□□□)	-13.993	0.003	0.9767	-0.174	---	---	**(6)**
Dishwashers	□ + □ × □□(□□□_□□□) + □ × □□(□□□□□□_□□) + □ × □□(□□□□□) + □ × □□(□□□□) + □ × □□(□□□□_□□□)	-18.920	0.459	0.013	1.122	0.020	-0.189	**(7)**
Freezers	□ + □ × □□(□□□□_□□□) + □ × □□(□□□_□□□) + □ × □□(□□□□□□_□□) − □ × □□(□□□□)	4.119	- 0.004	- 0.210	0.014	- 0.459	---	**(8)**
Clothes washers	□ + □ × □□(□□□□) + □ × (□□□□_□□□) + □ × □□(□□□_□□□)	-1.310	0.158	-7.521 e-05	-0.019	---	---	**(9)**
Clothes dryers	□ + □ × □□(□□□_□□□) + □ × □□(□□□□□□_□□□□) + □ × □□(□□□□) + □ × □□(□□□□□)	0.596	0.038	-0.002	0.072	0.019	---	**(10)**
Ranges	□ + □ ∗ □□(□□□□) + □ ∗ □□(□□□□□)	-6.107	0.550	0.593	---	---	---	**(11)**

Table 4: Statistical test results of developed models for the market penetration of major appliances

Appliance type	R-squared	Adjusted R-squared	Prob. (F-statistic)	Durbin-Watson stat.	Prob. a	Prob. b	Prob. c	Prob. d	Prob. e
Refrigerators	0.920960	0.907787	0.000000	1.410840	0.0008	0.0086	0.3240	0.1385	---
Dishwashers	0.985680	0.981384	0.000000	1.918807	0.0000	0.09222	0.0002	0.0235	
Freezers	0.920231	0.884779	0.000059	2.807209	0.0607	0.08859	0.0189	0.0683	0.0453
Clothes washers	0.938612	0.875196	0.000044	2.197458	0.0171	0.0635	0.0661	0.0798	---
Clothes dryers	0.960455	0.942880	0.000003	2.004643	0.0574	0.0940	0.0780	0.0815	0.0952
Ranges	0.997653	0.997227	0.000000	1.672624	0.0010	0.0477	0.0243	---	---

Table 5: Appliance annual market penetration growth rate in Alberta's residential market

Appliance type	Appliances per household annual market penetration growth rate (%) (2012-2050)
Refrigerator	+0.095%
Freezer	-0.494%
Dishwasher	+0.803%
Clothes Washer	+0.201%
Clothes Dryer	+0.211%
Range	Zero

Table 6: The impact of canceling the incentive program on average UEC improvement of major appliances - Incremental values vs 2015

Appliance type	2019	2020
Refrigerators	0.154	0.152
Dishwashers	2.841	2.818
Freezers	0.950	0.947
Clothes washers	2.755	2.487
Clothes dryers	0.150	0.148
Ranges	0.156	0.153