An Assessment of the Penetration of Low Carbon Technologies in the Energy Demand and Supply Sectors

by

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Abstract

The penetration of emerging low carbon energy technologies in the energy sector can provide significant opportunities to reduce greenhouse gas (GHG) emissions. An assessment of the market penetration of energy technologies can also help us understand their future adoption, which is critical in energy planning and management. There is limited research in this area. The overall aim of this research was to develop modeling frameworks to assess the penetration potential of low carbon energy technologies in various energy demand and supply sectors. The frameworks were applied to assess the penetration of low carbon technologies in the residential, industry, and electric power generation sectors. First, a comprehensive literature review was conducted. Then, appropriate methods to assess the market penetration level of low carbon energy technologies in different energy demand and supply sectors were determined. Hybrid models, comprising time series analyses, econometric models, and cost models, were then developed to assess the market penetration level of demand-side energy consumer technologies. A hybrid model was developed to assess the market penetration of low carbon energy technologies in the residential sector and was applied to analyze the adoption of high energy efficient appliances. This analysis focused on six major appliances – refrigerators, freezers, clothes washers, clothes dryers, dishwashers, and ranges. A new Market Penetration Model for Oil Sands Extraction Technology (MAPL-OET) was developed as a stand-alone tool to analyze the market penetration of commercial and emerging energy technologies in the oil sands sector. Finally, a hybrid model called MArket Penetration ModeLling of Energy technologies for Power Sector (MAPL-RET) was developed to assess the market penetration and market share potential of renewable energy technologies in a particular jurisdiction. The results from the residential sector case study for Alberta show that 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 of refrigerators will decrease from 560.9 kWh in 2012 to 460.8 kWh in 2050, which indicates an annual energy efficiency improvement of 0.5%. One of the key results from MAPL-OET indicates that carbon price can play a significant role in the market penetration of emerging oil sands extraction technologies. The shares of solvent-based extraction were 22.5%, 28.2%, 31.2%, and 38.1% in the zero, business-as-usual, low, and high carbon price scenarios by 2050, respectively. And finally, the MAPL-RET model outputs show that implementing a carbon price on fossil fuel electric power sources and incentives for renewable energies along with the phase-out of coal-fired electricity generation help increase the penetration of renewable energy technologies. This can reduce GHG emissions from 46.5 Mt of CO_2 eq. in 2020 to 23.6 and 29.1 Mt of CO_2 eq. per year in 2030 and 2050, respectively, compared to the business-as-usual case. The developed methods and approaches could help assess the impacts of policies related to incentives, subsidies, and carbon price on market penetration levels of low carbon energy technologies in the energy demand and supply sectors. The models developed in this study can help in energy forecasting and planning for policy formulation and decision making.

Preface

This thesis is an original intellectual product of the author, Saeidreza Radpour. Parts of this work are published as follows:

Chapter two was submitted for publication and is under review as Radpour, S., Mondal, A., Paramashivan, D., Kumar, A. Market penetration models for energy technologies: a review, 2020 (in review, Submitted to *Energy Strategy Reviews*). I was responsible for model development, analysis, and manuscript composition. A. Mondal and D. Paramashivan provided help in development of input data and assumptions. A. Kumar provided supervisory oversight, intellectual guidance, and support with the model development and manuscript composition.

Chapter three of this thesis has been published as a refereed journal publication: Radpour, S., Mondal, A., Kumar, A. Market penetration modeling of high energy efficiency appliances in the residential sector, *Energy*, Volume 134, 2017, Pages 951-961. I was responsible for model development, analysis, and manuscript composition. A. Mondal provided help in development of input data and assumptions. A. Kumar provided supervisory oversight, intellectual guidance, and support with the model development and manuscript composition.

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List of Abbreviation

a	Constant coefficient in each developed model and varies for variables
app_cpi	Appliance CPI
A(F)	Number of ultimate adoption of the new product
Adjusted R^2	Adjusted R-Squared is useful to analyze the fitting degree when the number of actual data is relatively high
AAE	Absolute average error
AB	Alberta
ADR	Active demand response
AESO	Alberta electric system operator
AGECC	Advisory Group on Energy and Climate Change
APH	Appliances per household
b	Constant coefficient in each developed model and varies for variables
bbl	Barrel
BAU	Business-as-usual
c	Constant coefficient in each developed model and varies for variables
C(i)	Constant coefficients in developed models

Ct_i	The price of carbon of item *i*
CAD	Canadian dollar
CAPEX	Capital cost
CC_i	The capital cost of item i
CER	Canada energy regulator
CL_i	The carbon cost of item i
CO_2	Carbon dioxide
CPI	Consumer price index
CPI_NG	Costumer price index of natural gas in the residential sector
CSS	Cyclic steam stimulation
d	Constant coefficient in each developed model and varies for variables
DER	Distributed energy resources
DW stat.	Durbin-Watson statistical test
e	Constant coefficient
elec_cpi	Electricity CPI
eq.	Equivalent
E	Total electricity demand

EHBE	Electromagnetic heating-based extraction
EC_j	Energy cost of technology j
EP(t)	Alberta's average electricity price in year *t*
EU	European Union
E_t	The plant energy output in year *t*
F	Number of technologies or products
F-statistic	Function statistic test
F(t)	Number of adopters at time t
Floor_HH	Floor area of single detached housing stocks per household
F^u	Maximum technology penetration or total potential of the specified technology
FASOMGHG	Forest and Agricultural Sector Optimization Model Greenhouse Gas
GDP	Gross domestic product
GDP_HH	Gross domestic production per household
GHG	Greenhouse gas
GJ	Gigajoule, equal to 10^9 J
GW	Gigawatt

GWh	Gigawatt hour
HVAC	Heating ventilation and air conditioning
HDD	Heating degree days
Income_hh	Household income
kW	Kilowatt
kWh	Kilowatt-hour
K	Number of competing technologies
ln	Natural logarithm
LCOE	Levelized cost of energy
LEAP	Long-range Energy Alternatives Planning
m	Potential market
m^3	Cubic metre
M	Million
MJ	Megajoule
Mt	Million tonne
MAPL-OET	MArket Penetration ModeL for Oil sands Extraction Technology

MAPL-RET	MArket Penetration ModeLling of Renewable Energy Technologies in Power Sector
MS_j	Market share of technology *j*
MW	Megawatt
MWh	Megawatt hour
nat_mig	National migration
N	Number of technologies or products at time t
N^u	Total potential of the specified technology or product
$NCI_{insitu}(t)$	New capital investment in in situ mining in year *t*
$NCI_{surf}(t)$	New capital investment in surface mining in year *t*
NEMS	National Energy Modeling System
NRCan	Natural Resources Canada
NSERC	Natural Sciences and Engineering Research Council
OC_i	The operating cost of item i
OECD	Organization for Economic Co-operation and Development
OLS	Ordinary least squares
OPEX	Operating cost

O&M	Operating and maintenance costs
p	Coefficients of innovators
p(t)	Alberta's heavy oil price in year *t*
P_B	Bitumen production
$P_{B\_insitu}(t)$	Bitumen production by in situ mining in year *t*
$P_{B\_surf}(t)$	Bitumen production by surface mining in year *t*
Popu	Population
ppl	Power plant lifetime
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
PJ	Petajoule - equal to 10^{15} J
q	Coefficients of imitators
r	Discount rate

R^2	*R-squared which* analyzes the fitting degree of the developed model
R&D	Research and development
SAGD	Steam-assisted gravity drainage
SBE	Solvent-based extraction
SCO	Synthetic crude oil
SD_NG	Natural gas demand in single detached housing stocks
SD_NG_Share	The share of natural gas demand in single detached housing stocks
Stat.	Statistic test
StatCan	Statistics Canada
SV	Student version
t	time
T	tonne
TOE	Tonnes of oil equivalent
TLCC	Present value of the life cycle cost
TWh	Terawatt-hour
u	Delay coefficient
unempl-rate	Unemployment rate

urban	Urbanization
US	United States of America
UEC	Unit energy consumption
UK	United Kingdom
$Weight_i$	The weight of item i
WCS	Western Canadian Select
x	The macroeconomic variable effective in market penetration modeling
x_1	Variable used in market penetration modeling
x_2	Variable used in market penetration modeling
x_3	Variable used in market penetration modeling
$x(\tau)$	Political and economic impact of market penetration
ºC	Degrees Celsius
ε	The residual value in each point
$	Dollar
v	Measure of market heterogeneity

Chapter 1 : Introduction

1.1. Background

Global energy demand has been increasing in recent decades and is projected to grow by 50% between 2018 and 2050 [1]. Strong socioeconomic development around the world is the major driver [2]. Greenhouse gas (GHG) emission mitigation has been identified as one of the major challenges of the 21st century [3] and it directly linked to the fossil fuel utilization. It has been observed that an increase in the global average temperature of about 1 ºC above pre-industrial levels has significant climate change impacts and natural disaster events such as flooding and wildfire in some countries [4]. The Paris Agreement aims to limit the earth's temperature to well below 2 ˚C above pre-industrial levels to minimize the threat of significant climate change by the end of the current century [5]. Achieving the Paris Agreement's objectives require actions – such as a transition to new energy efficient technologies and renewable energy systems – to reduce fossil fuel emissions to close to zero by 2050 [6, 7]. Greenhouse gas emissions from the utilization of fossil fuels in various energy demand sectors (e.g., residential, commercial, industry, transportation, and agriculture) is one of the main causes of GHG emissions and global warming. Therefore, the adoption of low carbon energy technologies has been recognized as one of the solutions to reduce energy intensity and hence mitigate GHG emissions in energy demand sectors [8].

A cursory glance at the energy intensity trend in most countries around the world shows that energy consumption per gross domestic production (GDP) declined between 1971 and 2010, with values between 0.13 and 0.26 tonnes of oil equivalent (TOE) per thousand dollars of GDP at purchasing power parity levels [9]. The world's energy consumption and GDP data from 1971 to 2010 show that the average annual rates of change in GDP, energy consumption, and energy intensity were 3.4%, 2.2%, and -1.2%, respectively [10]. To achieve sustainable development globally, the Advisory Group on Energy and Climate Change (AGECC) recommends that energy intensity be reduced by 2.5% per year, which is almost double the current rate. Changes in energy intensities have occurred almost steadily over the past 30 years and show global improvement in energy technologies and consumption patterns [11]. This improvement in energy intensity globally is primarily due to the penetration of efficient technologies on supply and demand sides [12]. But it took long time to achieve current penetration levels because of various factors such as imprecise energy system specifications, slow technological improvement, and lack of appropriate infrastructure [13, 14]. Hence it is important to articulate energy system specifications clearly and make necessary infrastructure available for the effective penetration of efficient technologies into the market. Market penetration modeling is one of the most effective means of analyzing the effects of GHG mitigation scenarios to meet local, national, and global climate change policies [15].

The market penetration modeling of efficient technologies in energy systems is critical in energy planning and plays a key role in predicting the development and commercialization of emerging energy technologies. The forecasts could serve as a guiding tool to business establishments, power utilities and refineries, power and fuel distribution companies, government agencies, entrepreneurs, and research centers [16, 17].

Using more efficient energy technologies in all of these sectors could be effective in both local and global greenhouse gas (GHG) mitigation. The global GHG emission intensity was 0.4 tonnes of CO_2 equivalent per thousand dollars of GDP in 2017, about 78% of which was from the production and consumption of energy in the transportation sector, non-renewable electricity generation, oil and gas production, and space heating and cooling [18]. In Canada, over 81% of

GHG emissions come from the energy sector because of higher energy consumption due to extreme temperatures and vast landscape [19]. Early estimates of penetration rates could help in the formulation of policies to define and meet GHG mitigation targets by controlling the energy intensity in different energy demand sectors and successfully achieve goals of global sustainable development [20].

Achievable energy technology penetration into the market can be broadly divided into three types: technical potential, economic potential, and market potential. These are shown in Figure 1-1 [21]. Technical potential is the technically practicable reduction in energy consumption and it refers to advanced commercial or near-commercial technologies with high energy efficiency. Technical potential does not consider the costs or the life of the technology. If all new investment and retrofitting are based on the most energy-efficient technologies, the amount of energy savings is the economic potential at that time. If the benefits and avoided costs increase, economic potential will increase. Economic potential is also known as welfare potential of energy saving. Market potential is the achievable energy saving through existing energy prices, technology, and end-users' preferences. Therefore, market potential considers social barricades as well as market imperfections [22].

With these definitions, the role of energy policy in improving energy savings can be easily understood. Energy end-use efficiency improvement can bring the economic and technical potentials closer to each other by removing the market barriers that keep market potential below economic potential.

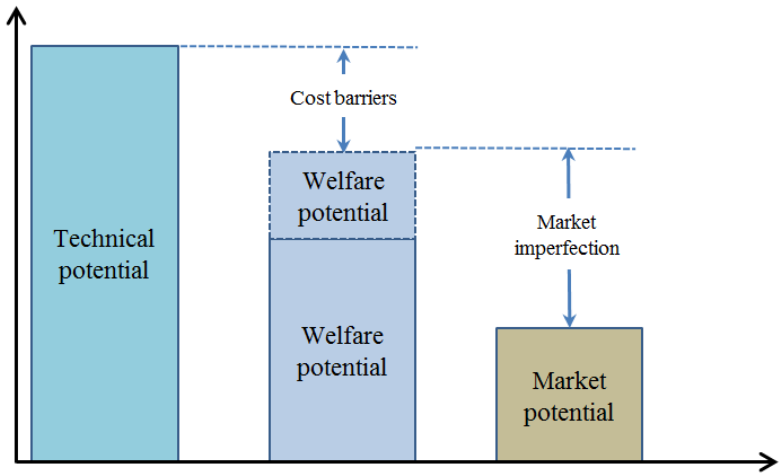


Figure 1-1: Types of achievable energy technology penetration into the market, adapted from Randall Spalding-Fecher (2004) with the permission of Elsevier Publishing Solutions (License number: 4784470897396)

Market penetration of efficient energy technologies and renewable energy resources plays a key role in global energy intensity improvement and GHG mitigation. For example, energy intensity in the past 40 years has decreased to an average annual rate of -1.2% [23]. This change is mainly due to the market penetration of efficient energy technologies as well as structural changes in the economy and improved conversion processes [24]. Financial incentives on energy efficient technologies and renewable energy sources for end-users can increase energy intensity and GHG mitigation [25]. That said, the market penetration of low carbon energy technologies is affected by technical factors, economic parameters, and governmental policies [26]. Also, there are different methods and tools to analyze the market penetration of energy technologies (see Tables 2-3 and 2-4). One of the major methodological challenges is how to consider the effects of different factors on market penetration modeling of energy technologies; some models consider technical factors, and others emphasize economic factors [27, 28]. In other words, there is a need for further methodological improvement to develop comprehensive models to analyze and consider all related major effective factors and parameters on market penetration modeling of low carbon energy technologies [29]. Moreover, new formulations on carbon price and incentives need to be an integral part of the market penetration model. These two factors can be local, national, or international [30, 31].

There is a variety of market penetration analysis models, such as subjective estimation methods [32], cost models [33], market surveys [34], diffusion models [35], historical analogy methods [36], and econometric models [36]. Several studies analyzed the market penetration of specific energy technologies at national and global levels. For example, photovoltaic technology market penetration was assessed in low voltage distributions [37]. The researchers summarized the key technical challenges and recommended a framework to explore the full range and technical methods. Another example is a review of instantaneous wind energy penetration in isolated electricity grids that highlighted the main limitations of the exiting models [38]. More recently, the potential of hydrogen to penetrate future energy systems was reviewed and analyzed by Chapman et al. [39]. Also, a review on methods for renewable energy sources' penetration recommended that using quantifiable and comparable factors in the modelling can provide precise results [40]. Combined models on renewable energy resources were reviewed and assessed by Rao and Kishore [42] and the importance of considering renewable energies' market potential, policies, and technological improvements in diffusion model parameters were highlighted. Also, combined market penetration models for alternative fuel vehicles were evaluated [41]. Several factors affect the robustness and reliability of market penetration models such as the availability of cost data and economic factors, the availability and accuracy of historical data, and the modeling approach [42].

1.2. Research gap

The thesis aims to address the following research gaps in the existing literature:

- Existing review papers on penetration models focus mostly on energy technologies, and there is no comprehensive and up-to-date review on market penetration methods covering a broad range of energy technology applications. There is a need to conduct a comprehensive literature review on the market penetration of energy technologies with the purpose of answering the following broad research questions: What are the state-of-the-art market penetration models for future energy technologies? What are the main advantages and disadvantages of each model? How do we choose a model from the existing methods? Is there a need for further methodological improvement?
- There is limited research on the market penetration of energy technologies in the residential sector. A few studies on the impacts of some methods on improving average energy efficiency have been done, for instance on labeling, incentives for purchasing high efficiency appliances, and pricing policy [43-46]. Comprehensive market penetration and market share models of the residential sector could provide insights into the penetration rates of efficient household appliances based on basic parameters and historical data [47]. However, there are no models that consider population, household income, technology expenditure, floor space per household, energy price, or immigration on the market penetration of energy technologies. Models that include these aspects can help assess the effects of incentives, capital and operating costs, and technology lifetime as well as inflation rate on market penetration of energy technologies.
- There is very limited investigation on the effects of technical and economic parameters on the market penetration and market shares of emerging oil sands extraction technologies and their impacts on GHG mitigation, energy saving, and energy intensity improvement. There are several GHG emission mitigation options in oil sands mining and extraction such as energy

management, upgraded control systems, and optimizing existing commercial recovery technologies. Reviewing the literature shows there has not been a big change in GHG emission intensity since 2004 [48]. Englander et al. stated that no signicant change will be observed in the emission intensity of the oil sands industry in the near future through retrofitting alternatives [48]. However, more aggressive clean in situ extraction technology adoptions such as Solvent-Based Extraction (SBE) and Enhanced Solvent Extraction Incorporating Electromagnetic Heating (EHBE) are indispensable in meeting local or global environmental limits in the oil sands industries [49]. Literature on the market penetration of energy efficient technologies for GHG mitigation in oil sands industries shows there are very few investigations in this field and no comprehensive models analyzing the effects of multiple parameters on market penetration and market share. There is a need to further investigate the market penetration of new technologies in this industry and assess the effects of global oil price, new capital investment, and carbon price on total oil sands production and the share of different technologies in this sector.

- The market penetration of energy efficient technologies and renewable resources in power generation can play a key role in GHG mitigation. There is very limited research on the market penetration of renewable energies. Some use experience curves to investigate, for instance, the potential cost of GHG emissions reduction through economies of scale following improved market penetration [50-54]. Learning curves are based on the reduced cost of new technologies and changes in output during the cost reduction period [55, 56]. The economic viability of renewable energy technologies compared to available alternatives has also been studied [57-60], and the results show that many factors affect the market penetration of renewable energy technologies in the electric power generation sector, including techno-economic factors, system infrastructure characteristics, and institutional factors such as provincial, national, local, and global protocols and conventions [26, 57]. The effects of government policies on renewable energy technologies' adoption have been studied through a system dynamics approach [58] and diffusion models [55, 56, 58]. Most studies analyzed a specific renewable energy source such as wind or solar [57]. However, very few market penetration studies consider technical and economic factors, which are critical when developing energy system models for market penetration and market shares of different technologies on the supply side, as are carbon price and governmental policies, and there is a gap in these aspects in analyzing the effects of changes in several aspects of the market penetration of electric power generation technologies.

1.3. Objectives of the research

The overall aim of this thesis is to develop a novel framework to analyze the market penetration of energy technologies in residential, industrial, and power supply sectors and to study the effects of different technical and economic factors on the market penetration of energy technologies, energy intensity improvement, and GHG mitigation potential in different energy sectors. The thesis, therefore, attempts to meet the general objective through the following specific objectives:

- Identify the pros and cons of existing market penetration models and develop a hierarchy framework to select the appropriate model and tool for a particular energy technology application;
- Develop a hybrid approach that incorporates time series analyses, econometric models, and cost models to forecast market penetration of electrical furnace heaters, energy efficient appliances in the residential and commercial sectors;

- Develop a comprehensive framework to assess the market penetration and market shares of emerging energy efficient technologies in oil sands mining sector including the analysis of the impact of carbon price and energy efficiency improvements on annual and accumulative GHG mitigation;
- Develop the production function between electricity demand and economic factors and analyze the impacts of economic incentives on the market penetration of low-carbon energy technologies in the electricity generation sector; and
- Investigate the impacts of economic incentives on annual and accumulated GHG mitigation from the energy demand and supply sectors;
- A case of Canada is conducted using the developed models.

1.4. Scope and limitations

This thesis focuses on four energy sectors – residential, commercial, industrial, and electric power generation. These sectors were chosen to cover three different types of energy systems, focusing on energy saving and GHG mitigation opportunities.

Operational parameters, such as known crude bitumen reservoirs, available electric power generation resources, energy intensity, the applicability of energy efficiency measures, and economic parameters (e.g., fuel price, carbon price, and inflation rates) are Canada- and province-specific.

There is limited data available on the economic and technical factors of emerging technologies. Moreover, changes in capital and operating costs of commercial technologies as well as their associated energy efficiencies in future are subject to uncertainties. Appropriate assumptions and different scenarios were formulated to develop uncertainties, and these are explained in each chapter.

The models developed for Alberta's residential, industrial, and power generation sectors can be used in other regions with some adjustments in economic input data, energy carrier price, carbon price, capital and operating cost, macroeconomic parameters such as GDP and population, and local government policies on electric power technologies.

1.5. Outline of thesis

The thesis is organized in six chapters; each chapter except the introduction and conclusion was written as an independent paper and submitted to peer-reviewed journals. This thesis is in the paper-based format. Hence, some conceptual and literature review might be repeated.

Chapter 2 is a literature review of studies on market penetration modeling of energy technologies and the state-of-the-art market penetration models for future energy technologies. The main advantages and disadvantages of each model, available tools and methods, and how to choose a model from the existing methods are investigated. In addition, a combined approach that incorporates time series analyses, econometric models, and cost models was developed and incorporated to forecast the market penetration of electrical furnace heaters in the residential sector in Alberta, Canada with a focus on single detached houses as a case study. This has been described in this chapter.

Chapter 3 investigates the market penetration of energy technology in the residential sector with a case study of major appliances in Alberta, Canada. This chapters describes the forecast the market penetration using econometric models. Modeling of the high-efficiency appliance shares and analysis of the impacts of incentives on energy efficiency improvement are described. Evaluation of the annual energy consumption by appliance are also covered.

In chapter 4, development of a new market penetration model for oil sands extraction technologies is described. This chapter also covers shows the use of the model as a stand-alone tool to analyze the market penetration of commercial and emerging energy technologies in the oil sands sector in Alberta, Canada. The application of the developed model for in situ bitumen mining technologies for forecasting their market penetration and market share from 2020 to 2050 is described.

Chapter 5 describes a new model developed to assess the impacts of policy measures on the market penetration and market share potential of renewable energy technologies. A case study for Canada is described. The impacts of carbon price and incentives on the market share of large-scale electric power generation from renewable energies for the years 2020 to 2050 are also discussed.

Chapter 6 summarizes the key findings and main conclusions from each chapter. Recommendations for future work also discussed in this chapter.

Chapter 2 : Market Penetration Models for Energy Technologies: a Review[1]

2.1. Introduction

The market penetration of emerging energy technologies provides significant opportunities to reduce global energy consumption and greenhouse gas (GHG) emissions [61]. Some emerging technologies have been developed to mitigate both environmental impacts caused by human activities and their socio-economic impacts [20]. Market penetration assessments of new energy technologies can help us understand their adoption in the future [49], which is critical in energy planning and management [62]. This is particularly helpful in predicting the development and commercialization of new energy technologies [63], which in turn could help business establishments [64], power utilities and refineries [16], power and fuel distribution companies [65], government agencies [17], entrepreneurs [66], and research centers [67].

Global energy intensity in the past 40 years has declined to an average annual rate of -1.2%, primarily due to energy efficient technology use [23]. Other reasons are structural changes in the economy and improved conversion processes [24]. Financial incentives for end users can increase the use of energy efficient technologies and renewable energy sources [25]. That said, the market penetration of energy technologies is affected by technical factors, economic parameters, and

[1] A version of this paper is submitted to the Energy Strategy Reviews journal - Radpour, S., Mondal, A., Paramashivan, D., Kumar, A. Market penetration models for energy technologies: a review. 2020 (in review, first round review completed and revised)

governmental policies. There are several market penetration analysis models, such as subjective estimation methods [32], cost models [33], market surveys [34], diffusion models [35], historical analogy methods [36], and econometric models [36]. Several authors have reviewed the market penetration of specific energy technologies at national and global levels. For example, Haque et al. reviewed high photovoltaic market penetration in low voltage distributions [37]. Their study summarized the key technical challenges and proposed a framework to explore the full range and technical methods. Weisser and Garcia also conducted a review of instantaneous wind energy penetration in isolated electricity grids and highlighted the main limitations of the exiting models [38]. More recently, Chapman et al. reviewed and assessed the potential of hydrogen to penetrate future energy systems [39]. A review by Andrychowicz et al. on methods for renewable energy sources' penetration suggested that using quantifiable and comparable factors in the modelling can provide precise results [40]. Rao et al. reviewed combined models on renewable fuel [42]. The study highlighted the importance of considering renewable energies' market potential, policies, and technological improvements in diffusion model parameters. Gnann et al. reviewed combined market penetration models for alternative fuel vehicles and concluded that market penetration models could be improved by considering refueling infrastructure, charging duration, and frequency [41]. The robustness and reliability of each market penetration model highly depend on several factors such as the availability of cost data and economic factors, the availability and accuracy of historical data, and the modeling approach [42]. Existing review papers on penetration models focus mostly on particular energy technologies. There is no comprehensive and up-to-date review on market penetration methods covering a broad spectrum of energy technology applications. To the best of the authors' knowledge, the latest similar review paper is the one by Rao et al., published in 2010 [42]. Hence, our review paper aims at compiling market penetration model of energy technologies with the purpose of answering the following broad research questions: What are the state-of-the-art market penetration models for future energy technologies? What are the main advantages and disadvantages of each model? How do we choose a model from the existing methods? Is there a need for further methodological improvement?

The paper, therefore, attempts to address these research questions through the following specific objectives:

- Perform an extensive literature review on existing market penetration models and identify their pros and cons;
- Develop a hierarchy framework to select the appropriate model for a particular energy technology application;
- Based on the review outcomes, develop a combined approach that incorporates time series analyses, econometric models, and cost models to forecast market penetration of energy technologies; and
- Assess the robustness of the new developed model by applying it to a case study in electrical furnace heaters in the residential sector in Alberta, Canada, including the ability of the proposed market penetration model to reflect the potential impacts of policies (i.e., incentives, subsidies, and tax).

2.2. Methodology

Analyzing available literature on methods and tools for market penetration modeling of energy technologies, categorizing them, and assessing the advantages, barriers, and challenges of each category can provide invaluable knowledge for future investigations either in academic or industrial perspectives. Within this context, a systematic review procedure was conducted to identify, retrieve, and analyze relevant scientific papers and reports available in exiting literature. This section describes the steps followed to conduct the literature review.

- In the first step, relevant publications were extracted mainly from the Elsevier database using a number of keyword combinations, these are, for example, market + penetration + energy + technologies; market + diffusion + energy + technologies, challenges + market + penetration + modeling + energy + technologies, market + penetration + methods, market + penetration + modeling + review, renewable + energies + market + penetration + modeling. To achieve a proper list of available literature, these keywords were searched in the title, abstract, and author-specified keywords. The search resulted in a total of 1602 publications which includes research articles, review papers, article in press, conference papers, books, and book chapters.
- In the second step, the title and abstract of 1602 publications were analyzed in detail to screen the related literature and to achieve intuition into the current available publications. The scope of the paper, model, and method (quality- and quantity-based) were the key considerations for the inclusion or exclusion of the studies.
- After a detail full text review of publications, market penetration approaches in the existing literature were categorized into 8 categories based on their input types and basic principles of models' concepts: subjective estimation methods, market surveys, historical analogy models, cost models, diffusion models, time series models, econometric models, and other models. Therefore, similar papers were removed, and this step led to 136 publications for further analysis.
- Once the market penetration approaches in the papers were categorized, each approach was further analyzed. The specific features of the approaches, pros, cons, and available tools and the related application areas were evaluated. One of the main challenges is how to select the

appropriate market penetration model for a particular energy technology. For that, a hierarchy diagram that prioritized the model choice based on the available information, tools and processes was developed.

Each market penetration model has its own advantages and disadvantages. Having combined features of different models could improve the reliability of market penetration modeling process. Based on the review outcomes, a new combined approach for the market penetration of energy technologies is proposed and a case study was applied to test the model. In the following sections, each aspect will be discussed in detail in its corresponding section.

2.3. A review of market penetration models and methods

Market penetration modeling of energy technologies can be complex process because of the variety of factors affecting the process. However, the modeling process highly depends on the technologies and their situation in the market. A market penetration model mostly follows an S-shaped curve over time [68]. Initially, a product penetrates into the market slowly, and its penetration rate is highest at the midpoint (or inflection point) of the curve; the penetration rate decreases over time, and at a certain point the market is considered saturated [69]. The market penetration path and dynamics vary considerably depending on the product type [70]. It can take several decades for energy technologies to move from their introduction into the market to the saturation level, especially for "long-lived" industrial technologies [71].

As shown in Figure 2-1, accumulated market penetration is the market share of a specific technology, and, at a specific point in time, the highest achievable market share is obtained [13]. Adopters are classified as "innovators/early adopters," "early and late majority," and "laggards" [42]. The time of adoption could determine where in the consumer adoption curve the technology was introduced in the market [72].

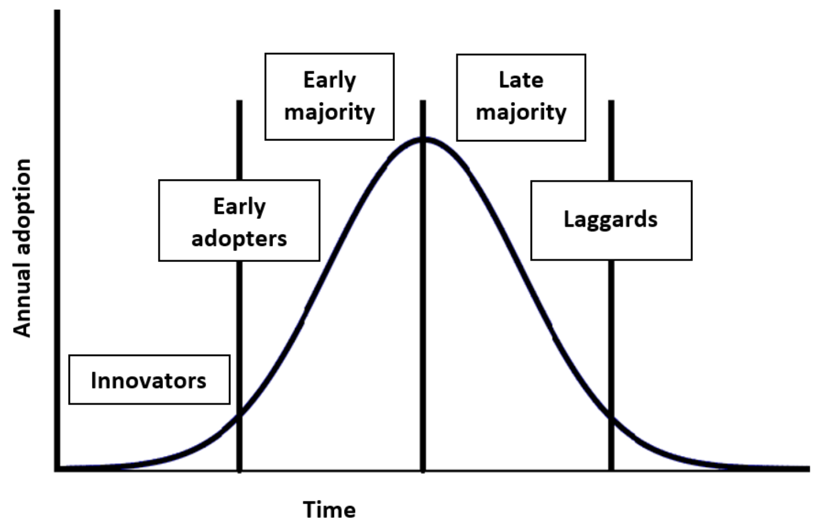


Figure 2-1: Market penetration curve – adopters vs. time. Adapted from Roger [13], used with the permission of Elsevier Publishing Solutions (License number: 3414870737469)

Many drivers influence an innovation's market penetration speed and saturation level, including innovation (types and characteristics) [13], the adopter (characteristics, attributes) [73], communication (information channels and media) [74], contextual factors (the social system, demographics, population, and communication behaviors) [75], the marketing activities that increase sales [76], and profitability (increasing the market penetration speed) [73]. Market response models have been developed with these drivers in mind. The models forecast the time period for the market penetration of a new technology and the achievable market share over a period of time.

One of the criticisms of market penetration forecasts is the uncertainty level [42]. Attempts have been made to decrease the level of uncertainty by developing mathematical models to study market penetration patterns [77], life cycle curves of products [78], and market penetration curves for new products [14]. Models that are more sophisticated have been developed to account for changes in the penetration curve. In the last 35 years, market penetration models have become more complex and include many variables, such as price [79], market potential [80], advertising and promotion [81], government support [82], and research and development (R&D) activities [83]. Existing methods and models are generally categorized into 8 broader categories and they are reviewed and discussed thoroughly in the following sections.

2.3.1. Subjective estimation methods

In general, researchers agree that it is inadequate to characterize a technique as subjective or non-subjective because all models have subjective assumptions [32]. However, there is a group of estimation methods based solely on subjective assumptions, and for this reason these methods are given a separate category in this review.

Subjective estimation methods can be straightforward in that they involve making decisions about introducing a product into the market based on outlooks and available data [84]. Subjective estimation models can also be based on formal decision-making processes such as the Delphi method, a method that relies largely on gathering information by distributing questionnaires to experts [85]. Subjective estimation can also be done by having an expert panel debate and discuss the various aspects of the technology and analyze the market penetration of a specific technology [86].

Subjective estimation methods consider some important factors in energy technology market penetration forecasting, such as technology characteristics, adopters, the market, and the effects of external organizations and government. These methods also consider effects related to the macro-context of the market [87]. An earlier study, for instance, showed that biogas engines had not penetrated the market and were not adopted by the intended end users, even though society viewed the technology as economically reasonable, because of an unfavorable macro-environment created by the government and an inappropriate pricing policy by the biogas engine manufacturers [88].

A review of published investigations on the use of subjective methods for energy technology market penetration and studies that used these methods shows that although these methods can be used for a broad range of energy technologies, including both emerging and mature ones including energy-saving innovations in the industrial sector [89], the use of biogas engines [88], energy intensity changes in commercial buildings [90], and the use of fuel cells in a specific region [91], subjective approaches do not produce statistically valid outputs. Moreover, subjective methods depend on an individual and their personal experience, so using these methods with two different groups of expertise would not necessarily give us the same results. Hence, the effectiveness of subjective models cannot be judged through a rigid and precise analysis process, nor is the subjective approach recommended for energy technologies with available historical data. Some other examples of subjective estimation methods used in energy technology market penetration are shown in Table 3.

2.3.2. Market surveys

Market research surveys collect market data of a specific technology using sampling methods such as questionnaires or databanks [34]. Government and private sector decision-makers' criteria on the specific energy technologies as well as preferences in technology adoption by end users are predetermined in such surveys in order to achieve a particular market size and product awareness [92]. Information for market surveys can be collected from organizations, businesses, decision-makers, and literature reviews [93].

Market surveys can help analyze the bottom-up perspective of adopters or investors in order to estimate and assess market penetration [94]. Moreover, market surveys can be based on the attractiveness and abilities of an individual technology [76]. Economic, technological, market, and institutional barriers to market penetration are also considered [95].

Although market surveys can help researchers assess the market of specific technologies (i.e., renewable energies [95] or clean coal technologies [96]), there are considerable obstacles to achieving reliable results. First, similar to subjective methods, market surveys are individual-dependent with different levels of authority that might not be sufficient to implement the forecasted changes into the market. Second, forecasted changes in the market can change because of forces not considered in the survey. Moreover, businesses plan secretly to be more competitive in the market. All of these obstacles aside, the results of a market survey are reliable for a short period. Some examples of market surveys in energy technologies for market penetration modeling are shown in Table 2-3.

2.3.3. Historical analogy models

Historical analogy is a forecasting method in which the penetration of a new technology is compared with that of a similar technology, assuming a comparable penetration pattern for both [36]. Knowledge of the penetration patterns of energy technologies in a particular region could be transferred to a similar region where there is insufficient information to forecast the penetration rate [97]. In addition, the penetration of an older energy technology could be used to forecast a newer, high-efficiency technology in the same region [98]. For example, the market penetration of fuel cell vehicles in a specific region could be similar to an earlier motive power substation in the same area [99].

While an historical analogy could be sufficient to forecast the penetration of similar technologies, its accuracy for loosely aligned technology is weak. This is one of the drawbacks of analogy models. Moreover, historical analogy models use time as the main variable and do not take into account other variables. Hence, where enough historical data are available, other methods that are more complex, such as time series or econometric methods, are preferred over historical analogy models [97]. Examples of historical analogy models used in energy technology market penetration modeling are shown in Table 2-3.

2.3.4. Cost models

Market penetration can be modeled using cost estimates. In such a model, several technologies in the same sector or sub-sector are analyzed and then costs are estimated and normalized. Through comparative normalization, a mathematical function is developed and annual technology market shares are calculated [33].

Cost models can use parameters such as the weighted averages of capital cost, net present value, levelized cost of energy, or payback period [16]. The total cost of each technology is a function of capital and operating and maintenance costs [100]. Modeling market penetration requires capital, operating, and maintenance cost estimates for the upcoming years [41]. In addition to parameters affecting capital and operating costs, the discount rate plays a significant role in cost market penetration modeling [101]. For example, the levelized cost of energy (LCOE) is a function of discount rate, lifespan of the technology, and total life cycle costs including capital, operating, and maintenance costs and can be calculated as follows:

$$LCOE = \frac{TLCC}{\sum_{t=0}^{ppl}\{Et(1+r)^{-t}\}} \qquad \textbf{Eq. 2-1}$$

where *LCOE* is the levelized cost of energy, E_t is the plant energy output in year *t*, *r* is the discount rate, *ppl* is the power plant lifespan, and *TLCC* is the present value of the life cycle cost. For power generation technologies, LCOE is the net present value of the unit cost of electricity generation over the lifetime of generating technology.

Although functions and variables used in cost models can make the modeling process straightforward, cost and associated variables are not the only parameters to consider. Other factors such as technical flexibility, resource constraints, and required infrastructure to develop a technology have a significant role in market penetration as well. In addition, cost models cannot capture the total available market because macro-economic variables affect it. Moreover, capital, operating, and maintenance cost estimates are not available for the long term for many technologies. Thus, cost models are not reliable if other factors are not considered and future costs of technologies are not available. Examples of cost models used in energy technology market penetration modeling are shown in Table 2-3.

2.3.5. Diffusion models

Diffusion models have a long history in market penetration modeling, starting in the 1960s. One of the first diffusion models is the Bass model (BM), developed by Frank Bass [35]. Diffusion models are a key part of market penetration modeling and there are many studies done using this method [102].

These models consider the adopters, that is, the innovators and the imitators, to estimate new product adoption in the market [103]. Those who are the first to use new technologies are innovators. Those who are influenced by previous users are the imitators [104]. Like other penetration models, the Bass model adoption rate follows the S-curve that illustrates innovator and imitative behaviors [13].

There are many different approaches for diffusion modeling [95]. To develop a mathematical model, it is assumed that F(t) is the number of adopters at time t and F^u is the maximum technology penetration possible. Therefore, the available potential for adoption is F^u-F(t). If the rate of adoption for the technology is b, technology adoption in one year can be calculated as follows:

$$\frac{Technology\ adoption}{Year} = (Annual\ rate\ of\ adoption) \times \left(\frac{Number\ of\ current\ adopters}{Maximum\ potential\ of\ adoption}\right) \times (Market\ adoption\ capacity) \qquad \textbf{Eq. 2-2}$$

Market adoption capacity is the difference between the maximum adoption potential and number of current adopters. If changes in technology adoption happen over a time period, Eq. (2-2) will be reformulated as follows [103]:

$$\boldsymbol{dF = b\frac{F}{F^u}(F^u - F)dt} \qquad \textbf{Eq. 2-3}$$

where F is the number of technologies or products at time t, F^u is the total potential of the specified technology or product, b is a coefficient, and t is time.

There are other investigations based on similar concepts and different assumptions leading to different diffusion models. They are shown in Table 2-1 [105].

Most of the available mathematical models for technology substitution are expressed as a multiplication of the ultimate adoption function (G(1-F)) and the remaining adoption function (A(F)). G(1-F) is the total potential of the specified technology or product and can be estimated based on a literature review, the population of the studied sample, or mathematical functions. A(F) is an estimation on how many adopters will ultimately purchase the new product. Therefore, A(F) is the critical part of a market penetration study in which the number of technologies or products changes over time. The values of both A(F) and G(1-F) are between zero and one [106]. Rationalized forms of various diffusion models are shown in Table 2-2.

In addition to economic parameters, advertisements and promotions can improve the adoption rate at the first stage of the market penetration process. Delre et al. developed a model to assess the impacts of promotions and advertisements on launching a new product in the market [69]. Although Delre's model has not been empirically demonstrated, its focus was on the time schedule of the promotions. Delre's model results show that promotions and advertisements have significant impacts on market diffusion. In addition, without promotional support or due to bad promotion timing [107], a product could fail to penetrate. Optimal promotion timing varies with the product, i.e., HVAC systems versus appliances.

The diffusion model is used for market penetration modeling, but this type of model needs a behavioral response, which is not available for each technology. Moreover, different innovations have their own diffusion process and are independent of other technologies [108]. It should be added that if the market penetration of a specific technology is related to that of another technology, diffusion models are not useful because they can only handle one technology at a time. In addition, diffusion models cannot capture supply limitations and assume that innovation behaviors are fixed and do not change over time. Hence, diffusion models can have limits not only on required data but also on the applicability of results for different technologies. Some examples of diffusion models used in energy technology market penetration modeling are shown in Table 2-3.

Table 2-1: Diffusion model classification adapted from Rao and Kishore [42] and used with the permission of Elsevier Publishing Solutions (License number: 3652090387409)

Category	Model type	Model equation
1. Models of cumulative adoption	1.1. Bass model	$\frac{dN}{dt} = (a + bN(t))(1 - N(t))$
	1.2. Cumulative log normal	$N(t) = N^u \int_0^t \frac{1}{y\sqrt{2\pi\sigma^2}} exp(-\frac{(ln(y) - \mu)^2}{2\sigma^2})dy$
	1.3. Cumulative normal	$N(t) = N^u \int_0^t \frac{1}{y\sqrt{2\pi\sigma^2}} exp(-\frac{(y - \mu)^2}{2\sigma^2})dy$
	1.4. Gompertz	$N(t) = N^u exp(-b(exp(-at)))$
	1.5. Log reciprocal	$N(t) = N^u exp(-\frac{1}{at})$
	1.6. Logistic	$N(t) = \frac{N^u}{1 + c\ exp(-at)}$
	1.7. Modified exponential	$N(t) = N^u - b\ exp(-at)$
	1.8. Weibull	$N(t) = N^u \left(-\exp\left(\left(\frac{t}{b}\right)^a\right)\right)$
	1.9. Generalized Bass model (GBM)	$\boldsymbol{N(t) = m \frac{1-e^{-((p+q)\int_0^t x(\tau)d\tau}}{1+\frac{q}{p}e^{-(p+q)\int_0^t x(\tau)d\tau}},\ 0 \le t < +\infty}$
2. Non-linearized trend and non-linear autoregressive models	2.1. Harvey	$LnN(t) - N(t-1) = a + b_1 t + b_2 \ln(N(t-1))$
	2.2. Floyd	$\left[\frac{1}{1 - N(t)}\right] + \ln\left(\frac{N(t)}{1 - N(t)}\right) = a + bt$
	2.3. Sharif and Kabir	$ln\left[\frac{N(t)}{1 - N(t)}\right] + \sigma\left(\frac{1}{1 - N(t)}\right) = a + bt$
	2.4. KKKI	$\left[\frac{bN^u - a^2}{bN^u}\right] \ln\big(a + bN^u N(t)\big) - (a+1)\ln(1) = b(bN^u + a)t$
	2.5. SBB (Sharma, Basu, Bhargava (1993)	$N(t) = N(t-1)\exp(a\big(N(t-1)\big))$

Remarks:

N is the number of technologies or products at time t; N^u is the total potential of the specified technology or product; u is the delay coefficient, $0 \le u \le 1$; m is the potential market; p and q are coefficients of innovators and imitators; $x(\tau)$ is the political and economic impact of market penetration and changes around 1. In the Bass model, $x(t)$ is equal to 1. If it is more than 1, the adoption rate is quicker over time; otherwise, it is not as fast as forecasted by the Bass model; t is time; and a and b are constants.

Table 2-2: Various forms of diffusion models, adapted from Jain et al. [106] and Rao and Kishore [42], used with the permission of Elsevier Publishing Solutions (License number: 3652090652035)

No.	Models	A(F)	G(1-F)
1	Coleman	A	(1-F)
2	Mansfield	bF	(1-F)
3	Bass	A+bF	(1-F)
4	Floyd	bF	$(1\text{-}F)^2$
5	Sharif–Kabir	bF/[1-F(1-e)]	$(1\text{-}F)^2$
6	(a) Easingwood–Mahajan Muller (NSRL)	bF^d	(1-F)
	(b) Modified NSRL	bF	$(1\text{-}F)^d$
7	Non-uniform Influence (NUI)	$(a+bF)^d$	(1-F)
8	Jeuland	(a+bF)	$(1\text{-}F)^{1+r}$
9	(a) Nedler	bF	$(1\text{-}F)^e$
	(b) Von Bertalanffy	$[b/[(1-e)]F^e$	$(1\text{-}F)^{1-e}$
10	(a)Generalized rational model (GRM-I)	bF/[1-F+eF]	(1-F)
	(b) Generalized rational model (GRM-II)	bF/(e+F-eF)	(1-F)
11	Other possibilities	$A+bF+rF^2$	(1-F)
		[a/(1+F)+bF]	(1-F)
		[a/(1+F)+bF]	$(1\text{-}F)^2$

Remarks:
F is the number of technologies or products at time *t*,
A, b, d and *e* are constants.

2.3.6. Time series models

A time series analysis analyzes a life cycle trend. The main difference between time series models and historical analogy models is that an historical analogy for the most part does not take into account variables not related to time, and time series models are based on both time and time-related variables such as economic or technical parameters [109]. Most of the technologies that successfully penetrate the market follow a similar pattern [110]. Those technologies in the same category and with the same use will have a more similar pattern, though the time required to reach the maximum market share can vary [111]. Time series models could help forecast the penetration of current energy efficient technologies [112]. These models are not only effective in forecasting new product penetration but also useful as tools to compare the results of other analytical methods

[113]. Time series analyses have been criticized in cases in which there is a thermodynamic, technical, or mechanical limitation [114].

Although time series models are straightforward and the method is well established, they are based on the continuation of an existing situation, but a particular technology may not continue to be used, especially in the long term. In addition, time series models cannot easily capture changes in prices and tax even if historical data is available. Moreover, the accuracy of time series models is poor; they do not explain the residuals, that is, the differences between actual data and model results in modeling, and can be a source of error. Hence, using time series analysis is limited to short-term planning for technologies without historical data on market penetration. Some examples of time series models used in energy technology market penetration modeling are shown in Table 2-3.

2.3.7. Econometric models

Econometric models model an economic theory through mathematics and statistics based on a relationship between a dependent variable and a group of independent variables. Econometric modeling uses a hypothesis to forecast future trends. Briefly, the steps in econometric modeling are: 1) developing an economic theory, 2) implementing statistical methods to estimate the parameters, and 3) estimating the model's accuracy [36].

Estimating model accuracy is often done by using direct and indirect approaches through appropriate statistical tests with a focus on residuals [115]. High residual values could make the models unreliable even if the most sophisticated models are used due to the nature of innovation [116].

In the direct approach, one econometric model is developed for the available market for a specific technology and another is developed to estimate the total market available for all technologies in a specific field including the considered technology and all competitor technologies [117]. The future market share of a specific technology is calculated by dividing the market for a specific technology by the total available market. In the indirect approach, the specific technology's market share is a dependent variable and is calculated based on the econometric function directly. The results of both methods should be the same, but their emphasis and implications are different. They are similar in that they both use historical data to estimate the functional relationship [118].

Econometric models are limited in their ability to make predictions for new technologies, but they can be integrated with diffusion and cost models to capture the market penetration potential of emerging technologies. Econometric models can be a part of a procedure for market penetration modeling for emerging technologies. One of the advantages of the econometric models is that the procedures, techniques, and steps of market penetration are documented. The main disadvantage is the need for detailed historical data, which may not be available for some products and technologies. Some examples of econometric models used in energy technology market penetration modeling are shown in Table 2-3.

2.3.8. Other models

Some models cannot be included in any of these categories and can be built by developing mathematical equations for specific regions or countries, analyzing the number of published patents in each scientific field, analyzing the experience curves (the relationship between production cost and cumulative production capacity), or evaluating the investment by different organizations on market penetration of specific technologies [52]. Moreover, models under this category can be developed for specific energy systems, for example, experience curves and economies of scale [50], stakeholders' view on the overall strategy to mitigate barriers to technology adoption [53], or analysis of policies and their impacts on new technologies, especially renewable energy technologies' adoption [119]. These techniques can help planners to assess the market penetration of energy technologies.

Table 2-3 provides application examples of the market penetration models for energy technologies

Table 2-3: Examples of market penetration modeling in energy system applications

	Applications	References
Subjective estimation methods	Energy-saving innovations in the industry sector	[89]
	The use of biogas engines in India	[88]
	Energy intensity changes in commercial buildings in the United States	[90]
	Market penetration of fuel cell technology in Iran	[91]
Market surveys	Renewable energy technologies in Maharashtra State, India	[95]
	The use of clean coal technology in China's power industry	[96]
	The role of public policy in the market penetration of wind energy	[120]
	The future prospect of photovoltaics and concentrated solar panels technologies	[121]
	Market penetration of renewable energy technologies in India	[122]
	Market penetration of heat pump water heater and development of the technology roadmap in Pacific Northwest, US	[123]
	Diffusion of renewable energy technologies in Italy	[124]
Historical analogy models	Market penetration assessment of renewable energy in Korea	[125]
	Early gasoline refueling methods and analogies for hydrogen	[126]
	Market penetration of carbon capture and storage	[127] [128]
	Energy innovation diffusion in the UK	[129]
	Penetration of clean coal technology and by analyzing the development history of this technology	[96]
	Market penetration of innovative efficient technologies in the EU's energy system	[130]
Cost estimation models	Market penetration of energy technologies by formulating pricing policies	[131]
	The effect of costs and prices on the market penetration of photovoltaics	[132]
	Market penetration of renewable energy technologies in South Korea	[133]
	Market diffusion of condensing gas boilers in the Netherlands	[134]
	Market penetration of heat pump technology in the residential sector	[135]
	The diffusion of natural gas consumption	[136]
	The lighting energy technology portfolio in the residential sector, Karnataka State, India	[137]
	The effects of short-term operational constraints on market penetration of renewable energy resources and long-term energy system planning	[138]

	Applications	References
	Analyzing the growth of shale gas production and carbon capture storage technologies by considering CO_2 taxes	[139]
Diffusion models	Diffusion of new and high energy efficient technology in steel industry	[140]
	Market diffusion of irrigation water pumps in India	[141]
	Diffusion of energy efficient technologies in the German steel industry	[142]
	Diffusion of energy-efficient technologies in general	[68]
	The importance of energy policy on market penetration of photovoltaics in Japan and Germany	[143]
	Energy innovation diffusion in the UK	[144]
	Market diffusion and management of biomass energy use in the residential sector	[145]
	Market diffusion of bio-digestion as a renewable energy technology in Kenya and Rwanda	[146]
	Market diffusion of wind power technology through a generalized Bass model (GBM) framework	[147]
	Market diffusion and technological substitution models for fuel cell vehicles in the United States	[59]
	Market diffusion model for emerging energy technologies	[103] [54]
	Market diffusion of solar photovoltaics technology in developing countries	[102]
	Market diffusion of wind energy technology in India	[148]
	Diffusion model for renewable energy technologies	[149]
	Developing a diffusion outlook based on socio-geographic observation in Sri Lanka	[150]
	Market penetration of energy technolgies by using myopic decision making - UK case study	[151]
	Analysis of fusion market entry by developing an agent-based power plant fleet model	[152]
	Market diffusion of bioenergy in Ethiopia by analyzing the behavioriak precursors in the decision process	[153]
Time series models	The penetration of appliances in the household sector based on macroeconomic drivers	[154]
	Forecasting the market penetration of ocean wave energy in the Pacific Ocean	[155]
	Market penetration modeling of renewable energy in Turkey	[156]
	Estimation of wind energy production based on the wind energy production time series	[157]
	Market penetration of fusion power in low carbon global electricity system	[158]
Econometric models	Diffusion of energy-efficient technologies in an energy system based on a sample of 38 countries	[159]
	Market penetration modeling based on the consumption profile of different customers in a Danish case study	[160]
	Market penetration of bio-hydrogen by econometric models	[161]
	Analyzing the on-shore wind energy capacity in the EU	[162]
	An econometric study on total and renewable energy outlook in Malaysia	[163]
	Using simulation-based integrated assessment model in climate change policy investigations	[164]
	Market penetration of energy-efficient electric motors	[16]

	Applications	References
Combined methods	Forecasting new energy technologies by analyzing historical data	[80]
	Market diffusion of energy-efficient technologies in the iron and steel sector	[165]
Other models	Estimating the penetration of biodiesel into the market through FASOMGHG[2]	[166]
	Market diffusion of environmentally responsive technologies based on the share of environmental patents and pollution abatement expenditures	[167] [168]
	Assessment of diffusion of energy technologies through experience curves	[169]
	The diffusion of renewable energies based on the investment in 26 OECD[3] countries	[170]
	The effect of more energy-efficient technologies on consumer adoption, specifically through improving the efficiency of vehicles in the UK	[171]
	Adoption of new energy technologies with higher efficiency in the residential sector across US property markets	[172]
	Analyzing the dynamics of load, generation, and assets for balancing the generation variability in a fully integrated European power market	[173]
	Energy transition and market penetration of energy technologies in the industry sector by The FORECAST model	[174]

2.4. Result and discussion

This study provides observations and remarks on the tools and processes used for energy technology market penetration, the modelling choice based on available information and lifetime of each technology, and the methodological advantages of combining cost, time series, and econometric models. The combined model was tested through a case study on electrical furnace heater penetration in the residential sector of Alberta, a western province of Canada.

2.4.1. Tools and process

The tools and processes used in market penetration models of energy technologies found in the literature review are summarized in Table 2-4 along with key observations and remarks.

[2] Forest and Agricultural Sector Optimization Model Greenhouse Gas

[3] The Organization for Economic Co-operation and Development

Key aspects of different methods and models and their associated tools, as presented in Table 2-4, can help investigators adopt an appropriate approach to market penetration analysis based on the available and required data and recommended tools. Moreover, some of the models can be used to analyze the results of other models if required data is available.

2.4.2. Model choice based on available information

Following the literature review, a hierarchy diagram was developed to select the appropriate method to assess the market penetration of new technologies based on the available tools and processes in each model. The major advantages and disadvantages of different methods, along with recommended methods of assessing market penetration of energy technologies, are illustrated in Figure 2-2. As shown in the diagram, there are considerable limitations for some methods, such as the inability to use subjective estimation models and market surveys for long-term forecasts and the likely unreliable results from using historical analogy models because some technologies may not have the same features as others.

Figure 2-2 illustrates the hierarchy used for selecting the most appropriate method for a specific intended application with its strong and weak sides. The results from the diagram could be interpreted as: when the answer to a question is "Yes," the corresponding model is considered to be the most appropriate. Moreover, as shown in the diagram (Figure 2-2), the more information provided for each technology, the more reliable the model and the longer the time horizon can be forecasted for a technology's market penetration, especially when cost estimation models, diffusion models, and econometric models are used. It is worth mentioning that it does not mean other models could not be considered. It is always recommended that other methods be checked to see how useful they are in case of limitations in individual research work or to initiate a new combined method for a specific project.

Table 2-4: A summary of tools, processes, key observations, and remarks on market penetration methods

Models	Tools and processes	Key observations and remarks
Subjective estimation methods	- Delphi - Panel - Brainstorming	- Combining Delphi and panel approaches helps attain results that are more reliable. - This approach could be applicable if there is little or no historical data available to use other market penetration models.
Market surveys	- Questionnaire (online or paper-based) - Databank analysis methods	- Based on the analysis of information from decision-makers.
Historical analogy models	- Learning through a literature survey	- This method is most suitable for a technology that has similar characteristics with mature technology already in the market.

Cost estimation models	- Developing cost models and analyses based on:
	    - Average cost of capital
	    - Net present value
	    - Total life cycle cost
	    - Levelized cost of energy
	    - Price levelization
	    - Internal rate of return
	    - Simple payback period
	    - Discounted payback period
		- Combining cost diffusion tools with time series analyses and market share models can provide reliable market penetration results.
		- Statistical tests help confirm the accuracy of the results.
		- Optimization models can be used to calculate the optimal points in scenario formulation.
		- A cost model can play a significant role in incentive analyses.

Diffusion models	- Mathematical models of cumulative adoption - Non-linearized trend and non-linear autoregressive models	- Help simulate promotional strategies. - Economic and political considerations could be included in the model. - Information about technology innovators and imitators is the key.

Time series models	- Simple extrapolation models
	    – linear trends
	    – exponential growth models
	- Autoregressive models
	- Autoregressive integrated with moving average models
	- Mixed autoregressive and moving average models
		- Time series models are based on similarities in the life cycle of different technologies.
		- These models are not only effective in forecasting the penetration of new products but also useful as tools to compare the results of other analytical methods.

Econometric models	- Ordinary least squares - Two-stage least squares - Generalized least squares - Nonlinear regression - Dummy variable technique - Seemingly unrelated regressions	- The procedures, techniques, and steps of energy technology penetration forecasting by econometrics models are well established. - It requires strong time-series macroeconomic information related to the technology.

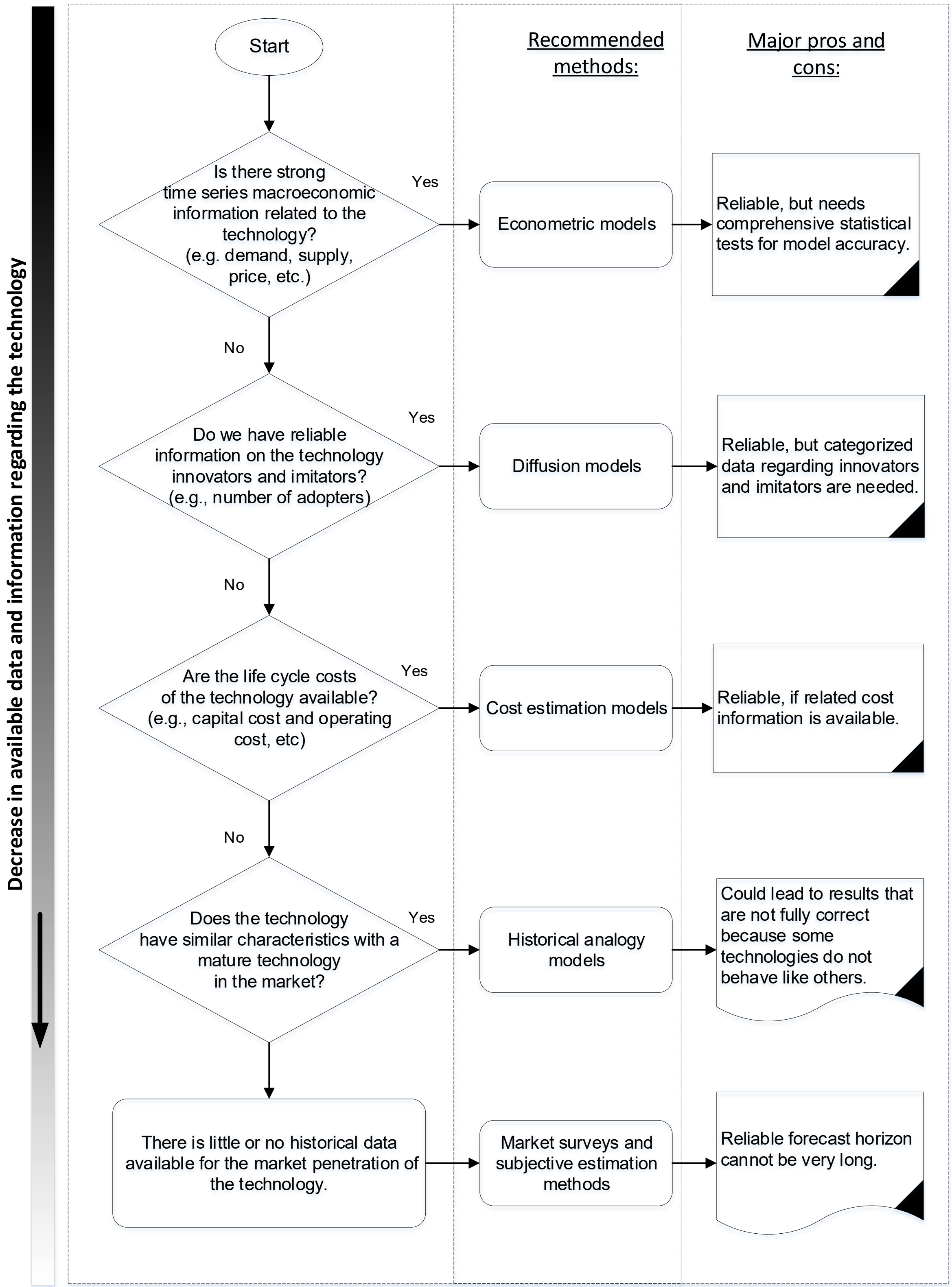


Figure 2-2: A hierarchy framework for selecting the most appropriate method for assessing the penetration of a particular energy technology

2.4.3. Model choice based on technology lifetime

Another result of the literature review is that some market penetration models can be recommended for different steps of a technology's lifetime, as shown in Figure 2-3. The figure can be used to select an appropriate means of developing an approach to market penetration modeling of energy technologies. If the technology is in its market introduction phase, subjective methods, historical methods, market surveys, and combined methods are recommended. After the technology is accepted in the market (market acceptance and getting mature phases), there are methods to analyze its market penetration such as: market surveys cost models, diffusion models, time series models and econometric models. Market survey can be used when the technology has matured.

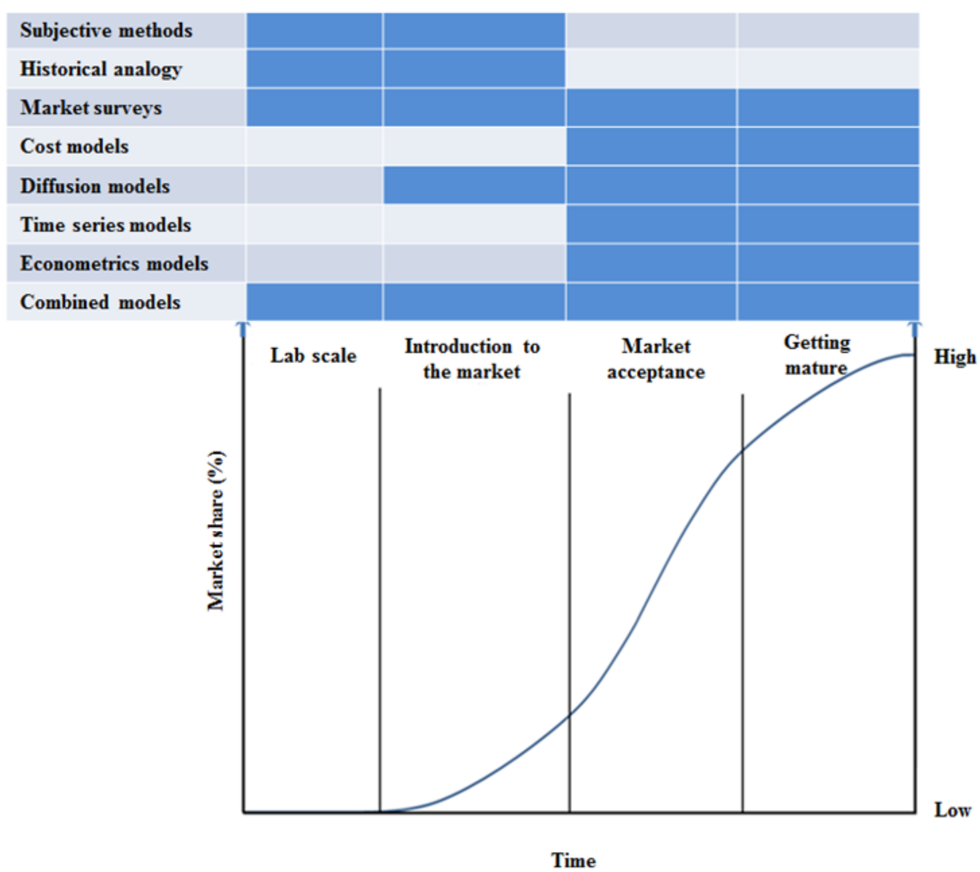


Figure 2-3: Different methods and models for each part of a technology's lifetime

2.4.4. Combining cost, time series analysis, and econometric models

As discussed in section 4.2, there are pros and cons in each market penetration modeling approach. However, it is possible to improve model reliability by combining methods. This approach combines different modeling methods and can compensate for the disadvantages of one method through the advantages of another, and are generally more efficient than any individual approach, even though the probability of the disadvantages of an individual approach having an impact on the results is not zero. The choice of models to be combined depends on the specification of the system studied.

There are different ways to combine market penetration models to improve reliability in modeling. One method that works well is the combination of economic and diffusion models. Teotia and Raju used both models sequentially for energy efficient electric motors and demonstrated that this approach may be more effective than using one method alone [16].

Following the model review, a combined approach that uses cost models, time series analysis models, and econometric models (see Figure 2-4) was developed in the current study. Combining econometric models with cost models offers the opportunity to consider the impacts of capital and operating costs in the market penetration modeling of energy technologies. Moreover, by combining approaches, one can develop different scenarios to analyze the impacts of incentives and taxes on the market penetration of high energy efficient technologies.

The developed combined model can mitigate the limitations of the cost models with the strengths of time series analysis and econometric models. The model calculates the total market using time series analysis and the econometric model. The model also analyzes the diffusion of each alternative by calculating associated costs and incomes including capital cost, operating and maintenances costs, probable incentives, and related taxes. Therefore, the combined model provides higher reliability than the individual models used to develop it.

In the first step, the variables' effects on the market penetration of different appliances are analyzed and individual variable probability tests are done using the least squares method and based on Pearson's correlation [175]:

$$\boldsymbol{Ln(y) = a + b \times Ln(x)} \qquad \textbf{Eq. 2-4}$$

where y is dependent variable, x is the potential independent variable, and a and b are constant coefficients in each case study and vary for different variables.

In the second step, more related parameters are selected and used in econometric diffusion functions. The general structure of the model is as follows [176]:

$$\boldsymbol{Ln(y) = a + b \times Ln(x_1) + c \times Ln(x_2) + d \times Ln(x_3) + \cdots} \qquad \textbf{Eq. 2-5}$$

where y is dependent variable, x_1, x_2, and x_3 are variables that will be used in market penetration modeling, and a , b, c, and d are constant coefficients in each developed model.

Eq. (2-5) is based on the Cobb-Douglas production function and analyzes the relationships between economic inputs and outputs with technology changes over time [177]. The production model provides analyses from the perspective of system-level studies based on a conceptual relationship between dependent and independent variables [178].

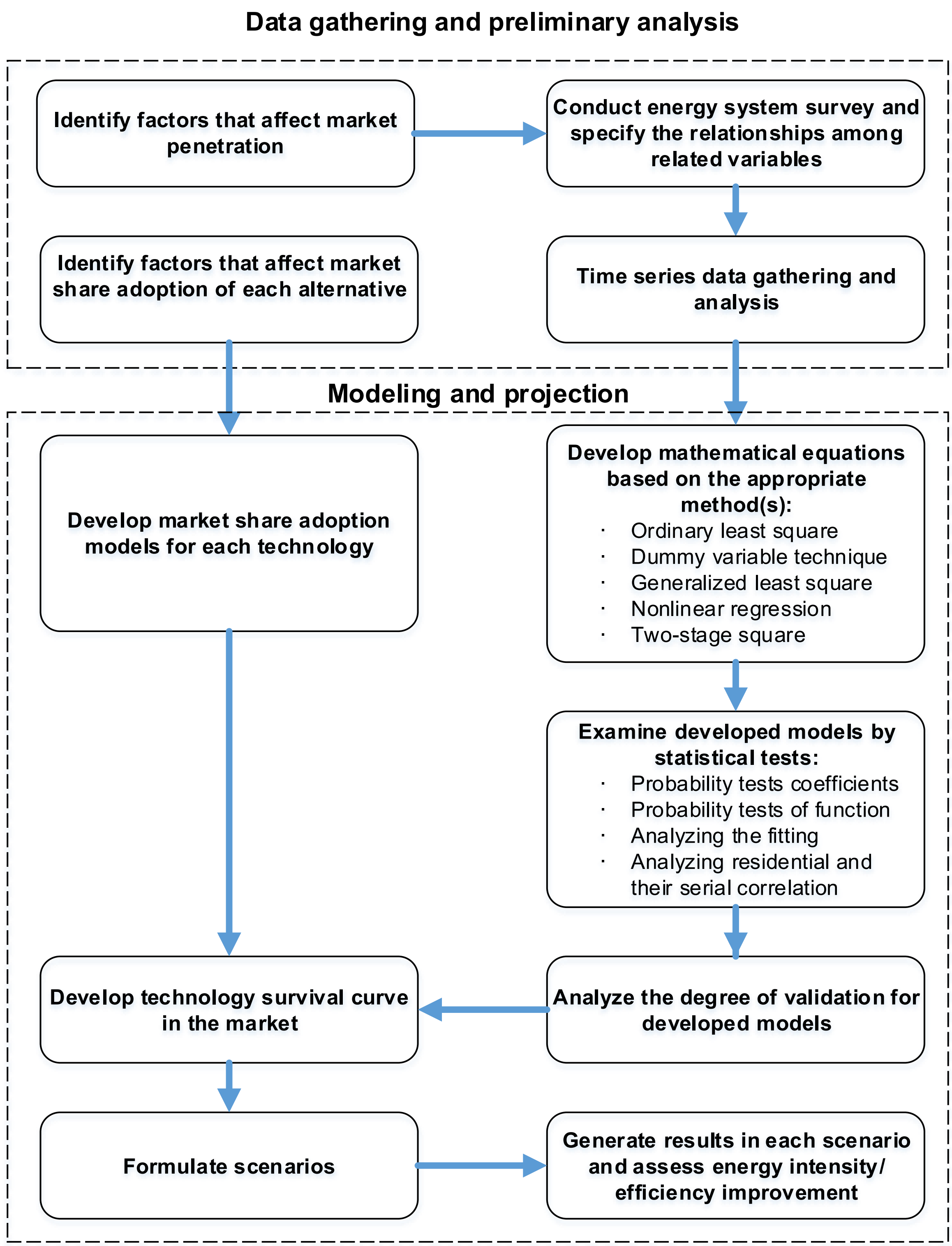


Figure 2-4: The combined model developed to assess the market penetration of energy technologies based on time series analysis, cost models, and econometrics models

In the third step, cost models are used to calculate the market share adoption of specific technologies by using a modified version of the energy-economy equilibrium model, described by Bataille et al. and Nyboer [179, 180], to analyze the market adoption rates of an individual technology:

$$MS_j = \frac{(CC_j \times \frac{r}{1-(1+r)^{-n}} + OC_j + EC_j + CL_j)^{-v}}{\sum_{k=1}^{K} (CC_j \times \frac{r}{1-(1+r)^{-n}} + OC_j + EC_j + CL_j)^{-v}} \quad \textbf{Eq. 2-6}$$

In the equation, MS_j is the market share of technology j, CC_j is the capital cost, OC_j is the maintenance and operation costs, EC_j is the energy cost, CL_j is the carbon emission cost, r is the discount rate, v is the measure of market heterogeneity, and K is the number of competing technologies. Based on these three equations, the market penetration of energy technologies is modeled with higher reliability because:

- The most important variables in market penetration modeling are selected based on Eq. (2-4) and statistical analysis.
- Probable changes in total market are analyzed by using the econometric model and validations.

The output of the cost models is modified based on Pearson's correlation and econometric models [175]. One of the main steps in the modeling process is to choose the most suitable approach and related tools.

In the next section, the results of the analysis of suitable methods and tools based on the available data and technology life cycle are presented. Also, the results of the market penetration analysis of electrical furnace heaters in the residential sector of Alberta, Canada, are presented as a case study based on the developed framework (shown in Figure 2-4).

2.4.5. Application of combined method to a case study

The developed combined model was applied to evaluate the market penetration of electrical furnace heaters in the residential sector of Alberta, Canada with a focus on single detached houses. Space heating energy consumption in 2015 in Alberta was 140.6 PJ (64% of residential sector energy consumption), comprising 90.08% natural gas and 2.54% electricity used in furnace heaters [181]. The share of electric furnace heaters has increased in recent years because of lower capital cost, quieter operation, longer durability, and quicker installation than conventional natural gas space heaters.

Energy use in space heating, provincial household growth, housing stocks, heating degree days, and space heaters per household were analyzed through econometric models and time series analysis. Figure 2-5 illustrates the time series of energy used in space heating, energy intensity, and heating degree days in Alberta.

As shown in Figure 2-5, space heating and floor space per household increase and energy intensity decreases over time. However, housing type does not change significantly over time and most new homes in Alberta built in the last two decades are single detached. Also, heating degree days have not changed much in the last two decades.

$$Ln(SD\_NG) = c(1) + c(2) * Ln(CPI\_NG) + c(3) * Ln(GDP\_HH) + c(4) * Ln(Floor\_HH) + C(5) * Ln(HDD) + c(6) * Ln(SD\_NG(-1)) \quad \textbf{Eq. 2-7}$$

$$Ln(SD\_NG\_Share) = c(1) + c(2) * Ln(SD\_Elec) + c(3) * Ln(GDP\_HH) + c(4) * Ln(SD\_NG\_Share(-1)) \quad \textbf{Eq. 2-8}$$

In the equations,

SD_NG: Natural gas demand in single detached housing stocks, CPI_NG: Costumer price index of natural gas in the residential sector,

GDP_HH: Gross domestic production per household,

Floor_HH: Floor area of single detached housing stocks per household,

HDD: Heating degree days,

SD_NG_Share: The share of natural gas demand in single detached housing stocks,

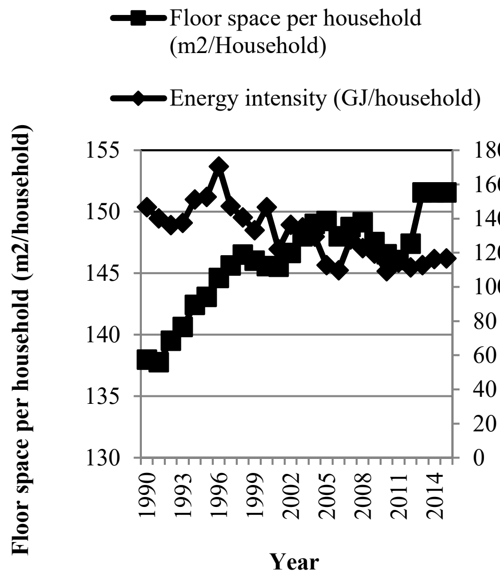
C(i): Constant coefficients in developed models

The developed mathematical econometric equations were verified through statistical tests and the degrees of validation were assessed. The constant coefficients in Eqs. (2-7) and (2-8) were adjusted using the statistical computation software Eviews 8 SV [182] and the results are shown in Table 2-5.

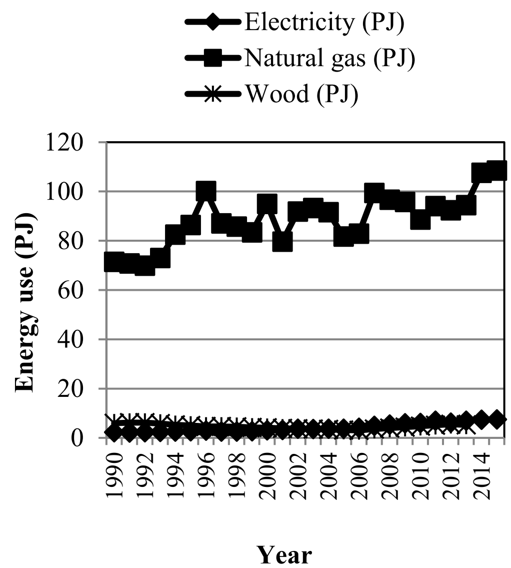
Table 2-5: Constant coefficients in the developed market penetration models

Eq.	c(1)	c(2)	c(3)	c(4)	c(5)	c(6)
2-7	-16.947	-0.137	0.522	3.211	1.113	0.032
2-8	0.072	-0.014	0.006	0.632	-	-

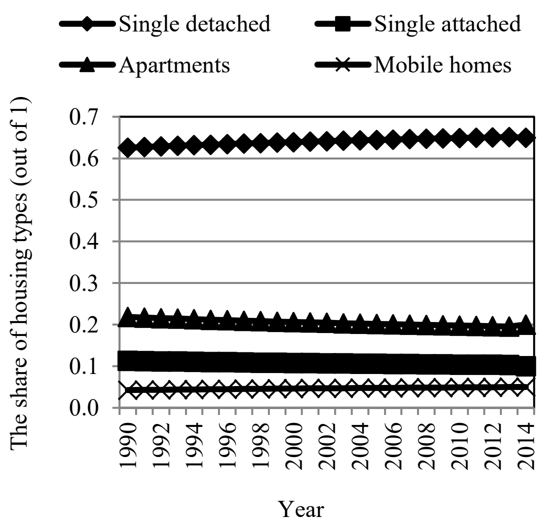
The constant coefficient values can be used not only in market penetration modeling but also in assessing the impacts of individual parameters on dependent variables. Each developed model was analyzed through statistical tests, and the results are shown in Table 2-6.



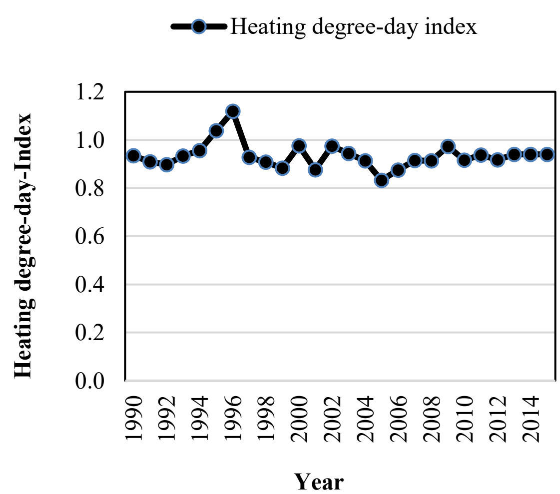
(a)



(b)



(c)



(d)

Figure 2-5: Time series of (a) energy intensity, (b) energy use, (c) housing types, and (d) heating degree-day index in Alberta

Table 2-6: Statistical analysis of the developed models and individual variables used in the market penetration assessment of electric furnace heaters

Statistical tests	Eq. 2-7	Eq. 2-8
Prob. a	0.0000	0.0109
Prob. b	0.0084	0.0026
Prob. c	0.0035	0.0150
Prob. d	0.0001	0.0002
Prob. e	0.0000	NA
Prob. f	0.0479	NA
R-squared	0.936	0.965
Adj. R-squared	0.915	0.959
Prob (F-statistic)	0.000	0.000
Durbin-Watson stat.	1.988	2.150

Probs are statistical tests used to evaluate the probability of the ineffectiveness of individual independent variables. All prob values are lower than 0.05; this shows that the variables play a significant role in modeling electric furnace heaters. The Durbin-Watson stat. is useful to analyze the serial correlation among the residuals. A Durbin-Watson stat. higher than 1.50 shows a low level of serial correlation; the developed models can pass the serial correlation test successfully. Therefore, the developed models not only were approved by the statistical tests but also covered the changes in actual data within a good level with an absolute average error of 1.03%.

Finally, the market share of electric space heaters was modeled based on capital cost, operating cost, lifetime, and technology applicability. Three different scenarios were formulated: high, medium, and low growth rate scenarios with 2.5%, 1.5%, and 1% annual GDP growth rates, respectively. The results of the market penetration modeling of natural gas and electricity demand for space heating in the residential sector are shown in Figure 2-6.

The results show that electricity demand in residential sector space heating could increase from 8.5 PJ in 2019 to 23.2 PJ in 2050 with no additional support and incentive from governmental and non-governmental organizations. The share of natural gas in space heating (93.1%) will decrease to 88% in 2050 if there is no major change in electricity and natural gas price trends in future.

Although there are no benchmark studies available for this case study, similar studies on electric space heaters show their market penetration and advantages in other regions. One of these investigations shows that electric heaters can improve energy efficiency in the residential sector. The study also showed that one of the advantages of electric systems is the global market penetration of Distributed Energy Resources (DER). Electricity is one of the major energy types generated by DER [183]. Moreover, flexibility in capacity size, generated power voltage, and trading mechanisms like contracts for ancillary services can provide a better opportunity for the adoption of electric heaters and consequently improve the energy efficiency in this energy sector.

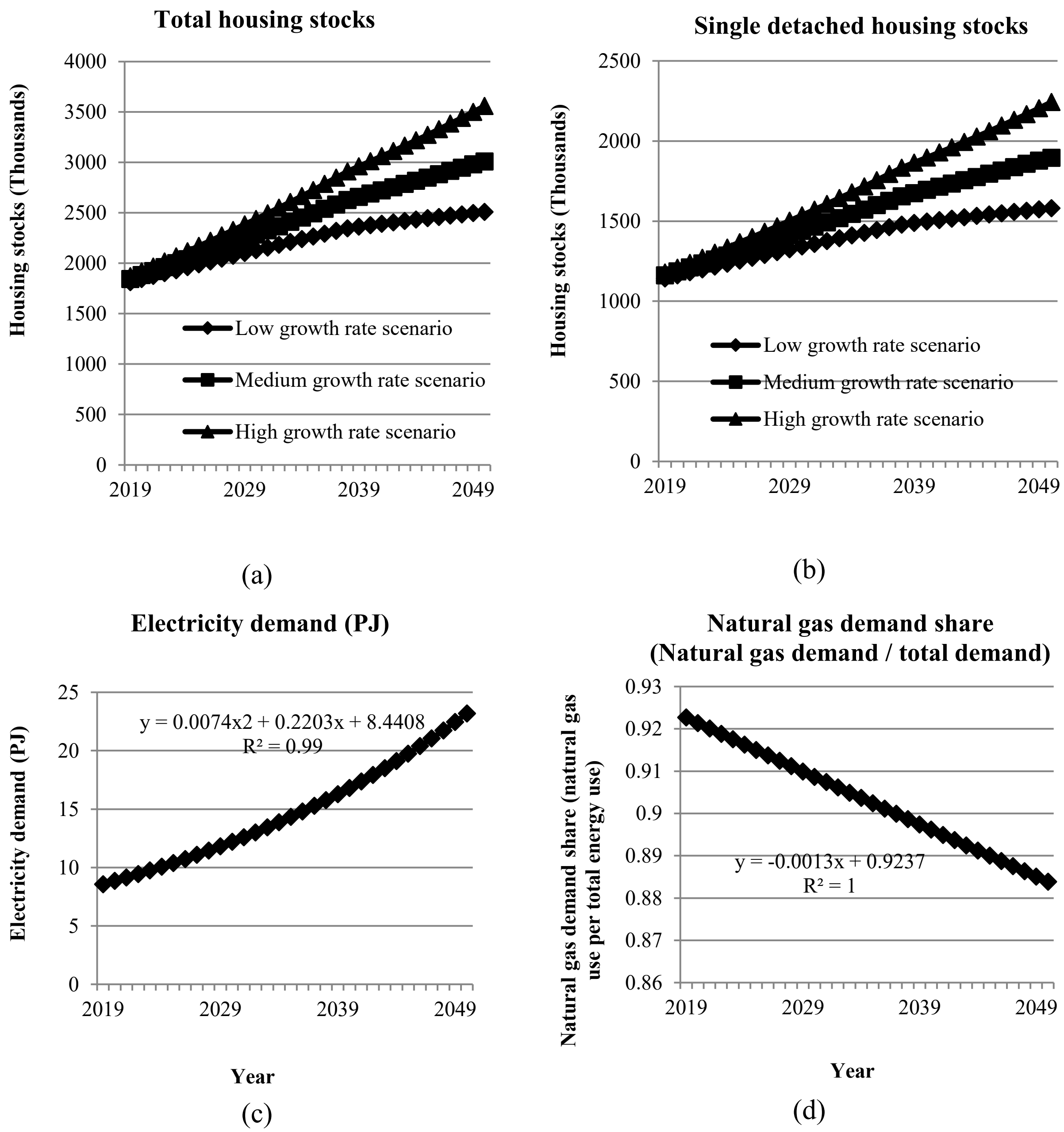


Figure 2-6: Market penetration of natural gas and electricity use in space heating in the residential sector with a focus on single detached housing: (a) total housing stocks, (b) single detached housing stocks, (c) electricity demand, (d) natural gas demand shares in Alberta from 2019 to 2050

Another study investigated the impact of electric heater market penetration by active demand response (ADR) in terms of electricity consumption and operational costs in end-user technologies such as heat pumps and electric resistance heaters [184]. The study concluded that the higher the number of participating consumers, the higher the flexibility of the system and the lower the overall operational costs.

The relevance of the current study is the development of an integrated model to analyze the impact of probable changes in energy carrier prices and incentives as well as in capital and operating costs. The analysis of the results shows that the developed combined model can properly evaluate the market penetration of energy technologies. The developed combined model can be employed in other energy jurisdictions if the required input data is available and the modeling process and relations among the input parameters can be established.

Developing new approaches based on computational models in those cases with enough detailed data is usually useful for a specific geographical region. Therefore, doing preliminary market surveys to determine the market situation is recommended. Performing preliminary market surveys is recommended especially for historical analogy models and time series models to avoid unreliable results that could come from assuming similarities in different technologies.

2.5. Conclusion

In this study, a systematic review was performed on market penetration modeling approaches with the purpose of assessing the state-of-the art models and tools, analyzing their key features, and evaluating their advantages and disadvantages. One of the key challenges is how to select the appropriate model for a particular application among the existing models. Bases on the review, this paper categorized existing models into 8 broader categories: subjective estimation methods, market surveys, historical analogy models, cost models, diffusion models, time series models, econometric models, and other models. An extensive review on the specific features of each approach is discussed in the paper and a hierarchy diagram was developed to help decision making on the choice of models based on the available information and tools. Models based on subjective estimation and market survey could be individual dependent and not reliable for long-term forecast. Historical analogy market penetration models can provide unreliable results because some technologies do not behave like others. Cost estimation, diffusion, and econometric models offer more reliable results and long-term forecasting if the required information is provided. The choice of one model over the other also depends on the maturity level of the technology.

The review results highlight the fact that reliable energy technology market penetration modeling is not based on an individual method but is a complex procedure influenced by a variety of factors. For example, in the case of new renewable energy technologies, government subsidies and incentives as well as technological improvement could play a key role in their development and future deployment. There are several market penetration models; however, they cannot accurately assess the potential impacts of different energy policies such as incentives, subsidies, taxes, and carbon levies. The future market penetration potential of new energy technologies could be modeled by developing combined models to achieve greater accuracy, especially for long-term forecasts.

Chapter 3 : Market Penetration Modeling of High Energy Efficiency Appliances in the Residential Sector[4]

3.1. Introduction

The improvement of energy efficiency in the energy demand sector has key impacts on energy consumption and GHG mitigation [185]. 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 [186]. 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 [187].

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 [188]. The province of Alberta has the highest per household energy consumption among the provinces [189]. Energy intensity by appliance in Alberta was 17.01 GJ per household in 2011, which put this province second in the country after Manitoba [189] 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 [190].

[4] A version of this paper was published in Energy journal - Radpour, S., Mondal, A., Kumar, A. Market penetration modeling of high energy efficiency appliances in the residential sector, *Energy*, 134, 2017, Pages 951-961.

In Alberta, 49% of refrigerators have the ENERGY STAR® label, which is a consumer icon in the Canadian marketplace [191]. The ENERGY STAR product label identifies products that are qualified as high efficiency [192]. These products have higher energy efficiency than regular ones and are considered energy efficient [193]. Under an agreement with the US 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 [194]. 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 [194]. 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) [195].

Market penetration and market share models could provide insights into the penetration rates of efficient household appliances based on basic parameters and historical data [47]. 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 [196]. 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 [43-46]. 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.

3.2. 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 3-1 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 Natural Resources Canada (NRCan) [189] and Statistics Canada (StatCan) [195]. Some of the key parameters considered are: population, household income [190], electrification, urbanization, consumer price index (CPI) [190], international and inter-provincial immigration to Alberta [197], unemployment rate [198], and people's awareness of the benefits of high energy efficiency appliances [199]. Other parameters, such as look, color, and style, which affect the adoption of appliances, were not considered in this study.

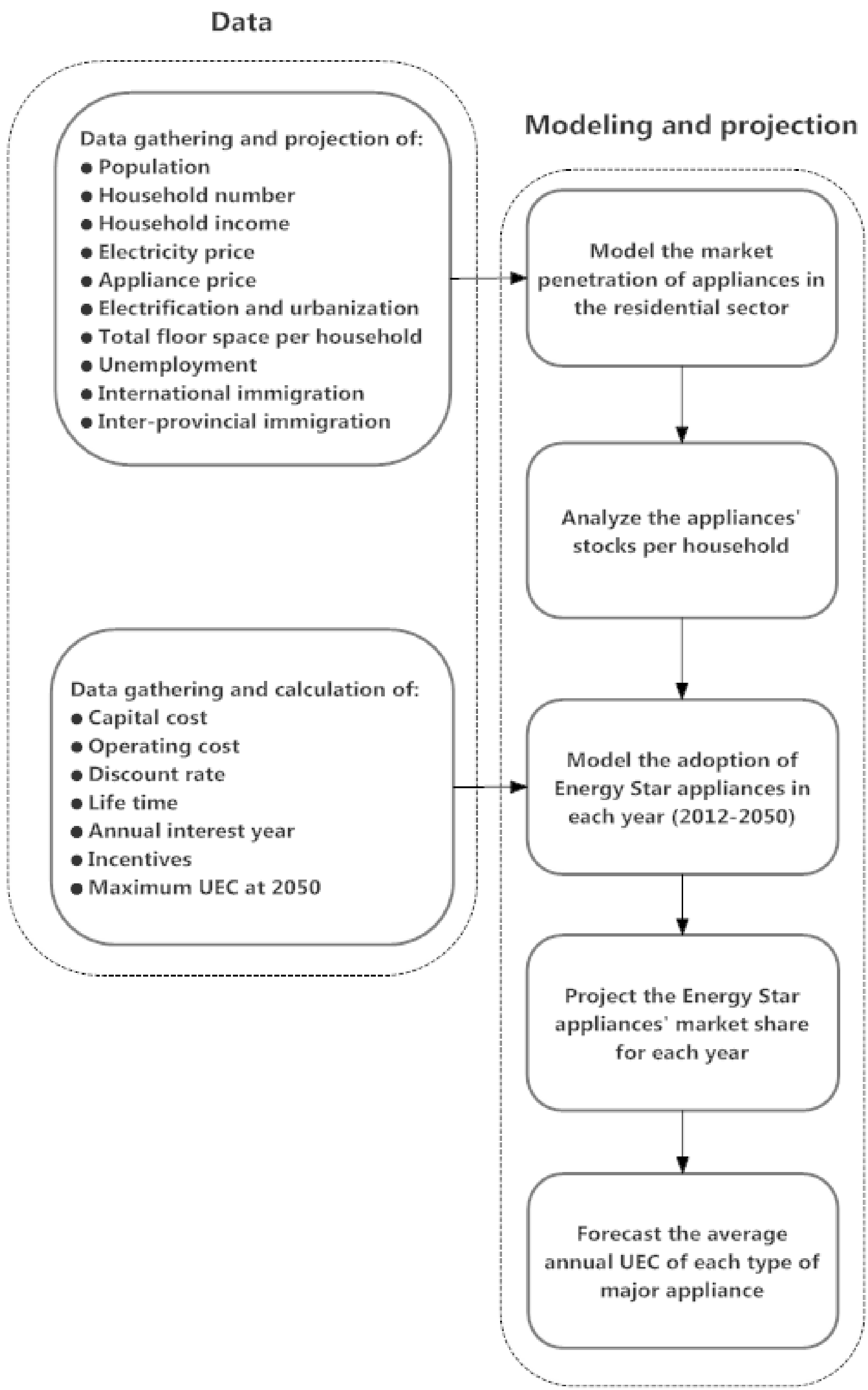


Figure 3-1: The method used in this study

3.2.1. 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 [200]. No one approach can be used for all circumstances. Models that are more complex make more reliable results, but they usually need more data [201]. Subjective estimation methods are used if there is little or no historical data available for related technology [196]. 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 [202]. For those technologies with two types of adopters (innovators and imitators), diffusion models could be a good option [42]. 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 [203]. 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 (Eq. (3-1)) [175]:

$$\boldsymbol{Ln(APH) = a + b \times Ln(x)} \qquad \textbf{Eq. 3-1}$$

where

APH is appliances per household;

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

a and b 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 [176]:

$$\boldsymbol{Ln(APH) = a + b \times Ln(x_1) + c \times Ln(x_2) + d \times Ln(x_3) + \cdots} \qquad \textbf{Eq. 3-2}$$

where

x_1, x_2, and x_3 are variables that will be used in market penetration modeling; and

a , b, c, and d 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 [177]. 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 [204]. The production model provides analyses from the perspective of system-level studies based on a conceptual relation between dependent and independent variables [178]. The developed mathematical equations were verified through statistical tests and were used in market share modeling and energy efficiency improvement analysis [205]. In addition, a sensitivity analysis was done to determine the effects of changes in each independent variable on the mathematical equation function [206].

3.2.2. Market share modeling

As shown in Figure 3-1, 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 [207].

The process for a market share analysis is applied to both new equipment purchases and decisions to replace existing appliances [201]. Competing technologies for a particular appliance are weighted based on capital and operating costs [208]. Market share for each appliance is calculated using Eqs. (3-3) and (3-4) [209]:

$$\boldsymbol{Market\ Share_i = \frac{Weight_i}{\sum Weight_i}}$$ **Eq. 3-3**

$$\boldsymbol{Weight_i = e^{(a\times CC_i)+(b\times OC_i)}}$$ **Eq. 3-4**

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) [209]. NEMS's model is the most influential energy model in the United States and has been used by the US Energy Information Administration to develop long-term forecast of energy consumption in the country [209].

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.

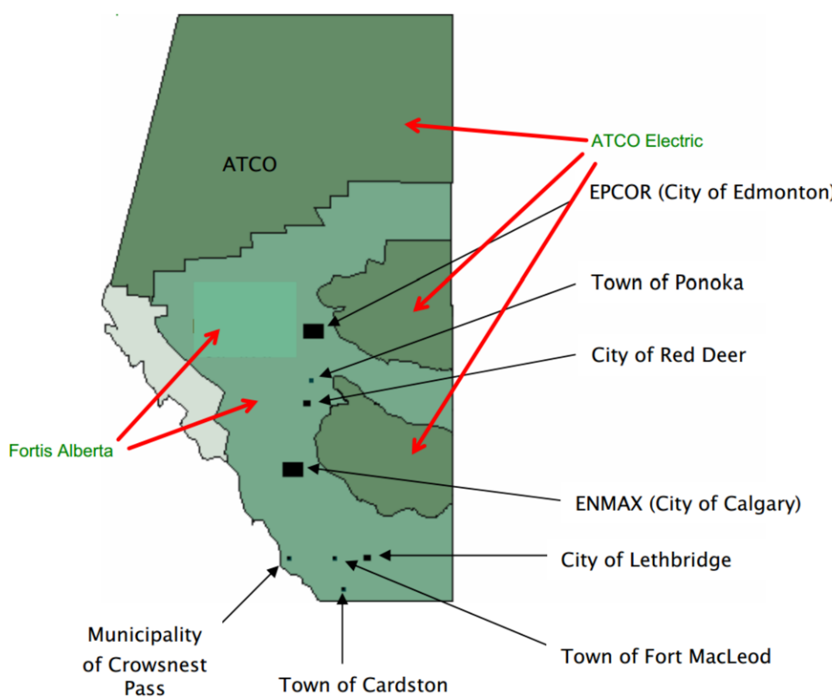


Figure 3-2: Alberta's electric distribution system's owners. Copyright obtained through personal communication with Gordon Howell [210]

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 3-2, 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.

3.3. Model statistical tests and validation

The analysis of different variables affecting the market penetration of appliances is based on Eq. (3-1). 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 3-1.

Table 3-1: 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

The fitting parameters in Eq. (3-1) were adjusted using the statistical computation software "*Eviews 8 SV*" [211]. 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 [211]. In Table 3-1, 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 3-1 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 [211]. The values of "R-squared" for each variable have been shown in Table 3-1.

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 [211]. The values of "R-squared" and "Adj. R-squared" in Table 3-1 show that "population," "household income," and "appliance CPI" are more effective than other variables in developing market penetration models for refrigerators (Table 3-1).

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% [211]. As shown in Table 3-1, 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 Eq. (3-5) [212].

$$\mathrm{DW} = \frac{\sum_{i=2}^{N}\left(\hat{\varepsilon}_i - \hat{\varepsilon}_{i-1}\right)^2}{\sum_{i=1}^{N}\hat{\varepsilon}_i^2} \quad \textbf{Eq. 3-5}$$

ε is the residual value in each point. The values of DWs lower than 1.0 are evidence of positive serial correlation [211].

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 3-1, 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 3-3.

An analysis of the graphs in Figure 3-3 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.

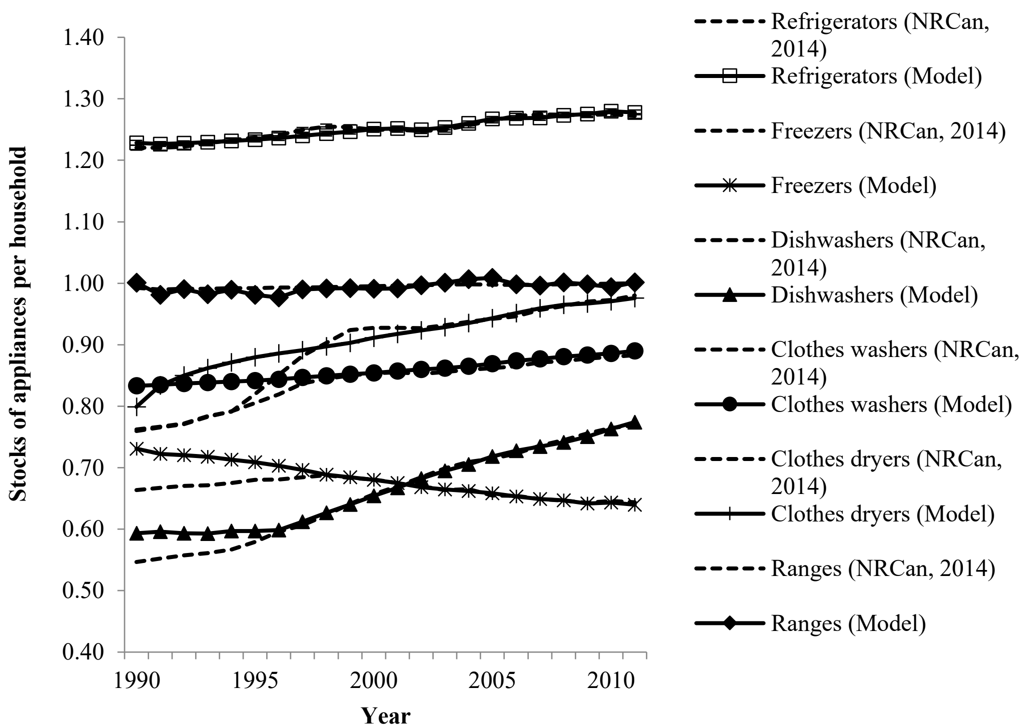


Figure 3-3: Validation results for market penetration modeling of appliances (1990-2012)

Table 3-2: 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 3-2 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.

3.4. 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.

3.4.1. 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 3-3. Table 3-4 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 3-3 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.

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

Appliance type	Econometric penetration model	*a*	*b*	*c*	*d*	*e*	*f*	*Eq.*
Refrigerators	$a + b \times Ln(popu) + c \times Ln(income\_hh) + d \times Ln(elec\_cpi)$	-13.993	0.003	0.9767	-0.174	---	---	3-6
Dishwashers	$a + b \times Ln(app\_cpi) + c \times Ln(income\_hh) + d \times Ln(urban) + e \times Ln(popu) + f \times Ln(elec\_cpi)$	-18.920	0.459	0.013	1.122	0.020	-0.189	3-7
Freezers	$a + b \times Ln(elec\_cpi) + c \times Ln(app\_cpi) + d \times Ln(income\_hh) - e \times Ln(popu)$	4.119	- 0.004	- 0.210	0.014	- 0.459	---	3-8
Clothes washers	$a + b \times Ln(popu) + c \times (elec\_cpi) + d \times Ln(app\_cpi)$	-1.310	0.158	-7.521 e-05	-0.019	---	---	3-9
Clothes dryers	$a + b \times Ln(nat\_mig) + c \times Ln(unempl\_rate) + d \times Ln(popu) + e \times Ln(urban)$	0.596	0.038	-0.002	0.072	0.019	---	3-10
Ranges	$a + b * Ln(popu) + c * Ln(urban)$	-6.107	0.550	0.593	---	---	---	3-11

Table 3-4: Statistical test results of developed models for 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	---	---

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 3-4 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 3-4.

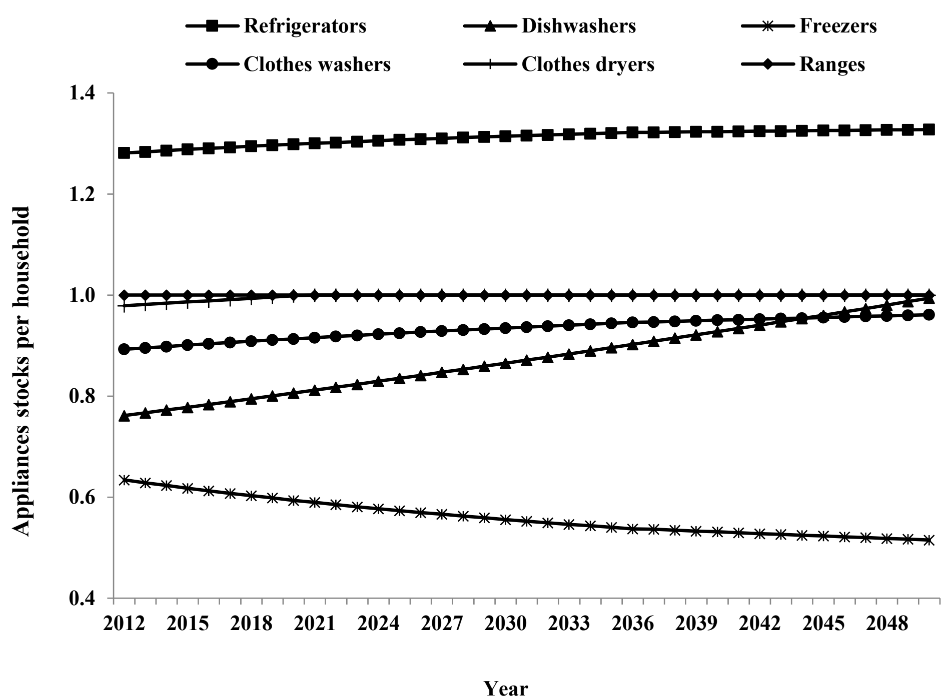


Figure 3-4: Projected market penetration of major appliances per household in Alberta's residential sector (2012-2050)

An analysis of Figure 3-4 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.

Table 3-5: 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

The total appliance penetration growth rate during the study period is shown in Table 3-5. 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 [213].

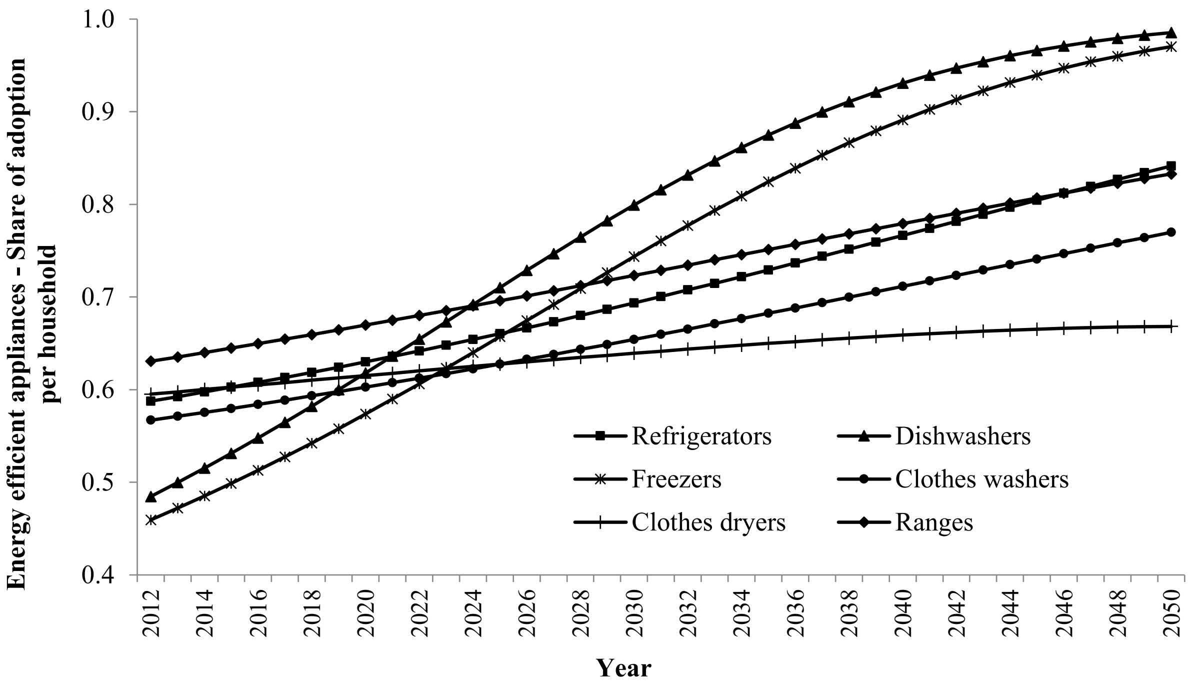


Figure 3-5: The adoption shares of high energy efficiency appliances (2012-2050)

As shown in Figure 3-5, 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 [214].

3.4.2. 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 US shows that there have been few such incentives programs in recent years [215].

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 3-6.

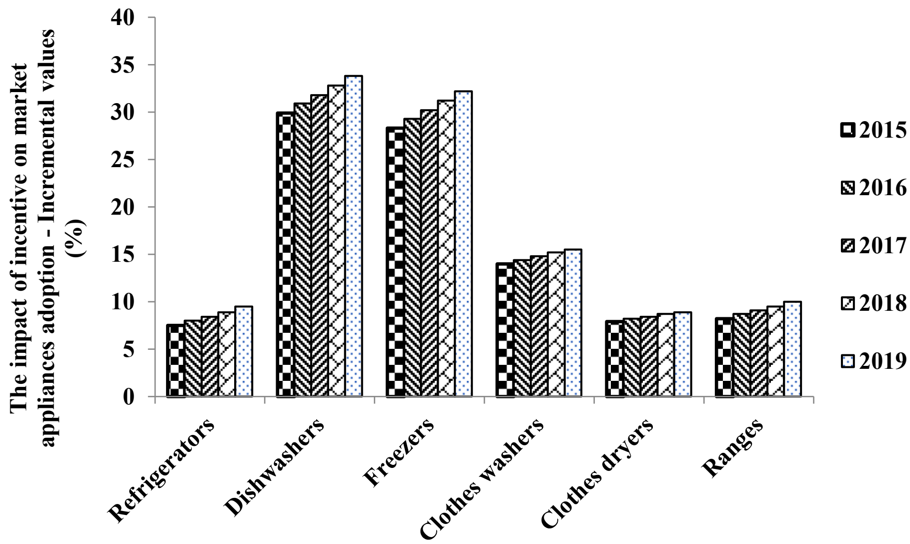


Figure 3-6: The impact of CAN $300 incentive in market penetration of high efficiency appliances from 2015 to 2019 vs 2014 values

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 3-6, 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 3-7. The incremental impact of incentives on UEC improvement rather than business-as-usual scenario has been shown in Figure 3-8.

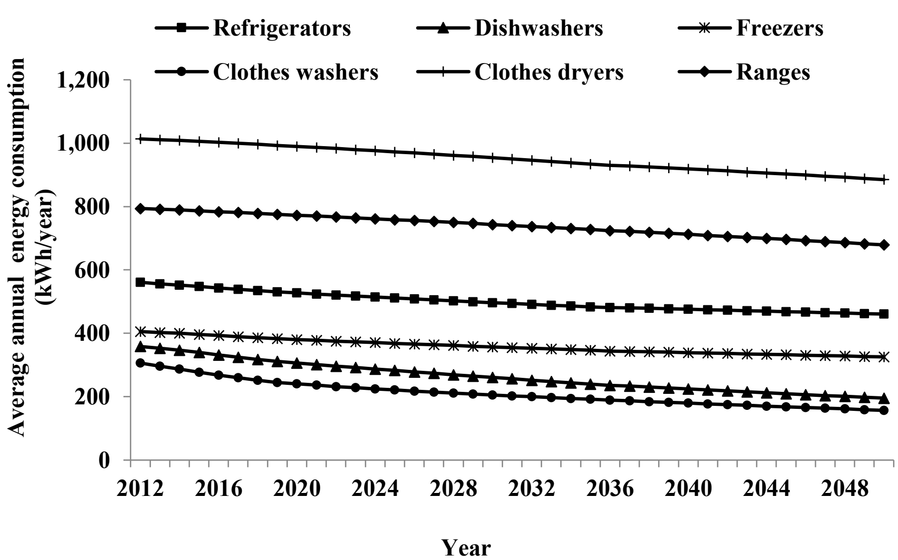


Figure 3-7: Average annual energy consumption of appliances based on the business-as-usual scenario with the incentive program (2012-2050)

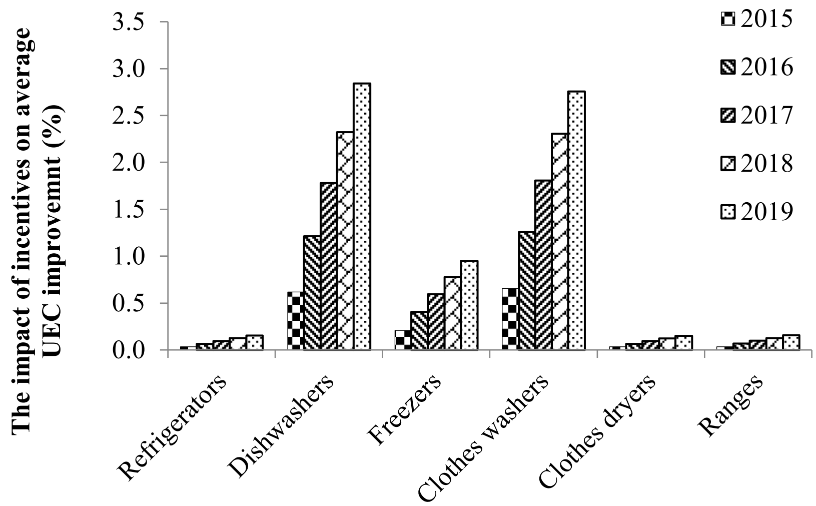


Figure 3-8: Incremental impact of incentives on average UEC improvement from 2015 to 2019 vs 2014

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 3-6). An analysis of the results shows that the impact of canceling incentives is higher for clothes washers and dishwashers than other appliances.

Table 3-6: The impact of canceling 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

3.4.3. 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 3-9.

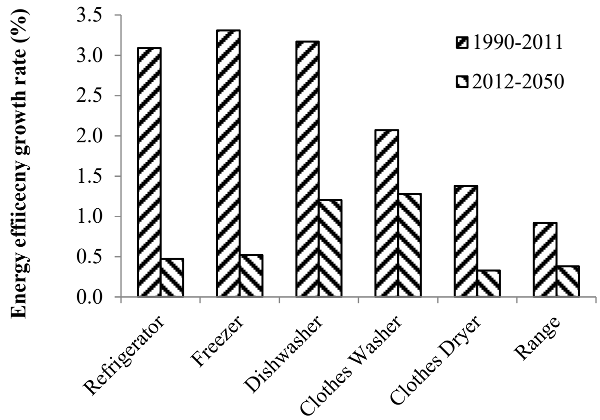


Figure 3-9: Annual average percentage growth rate in energy efficiency for each appliance from 1990 to 2011 and from 2012 to 2050

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 3-10.

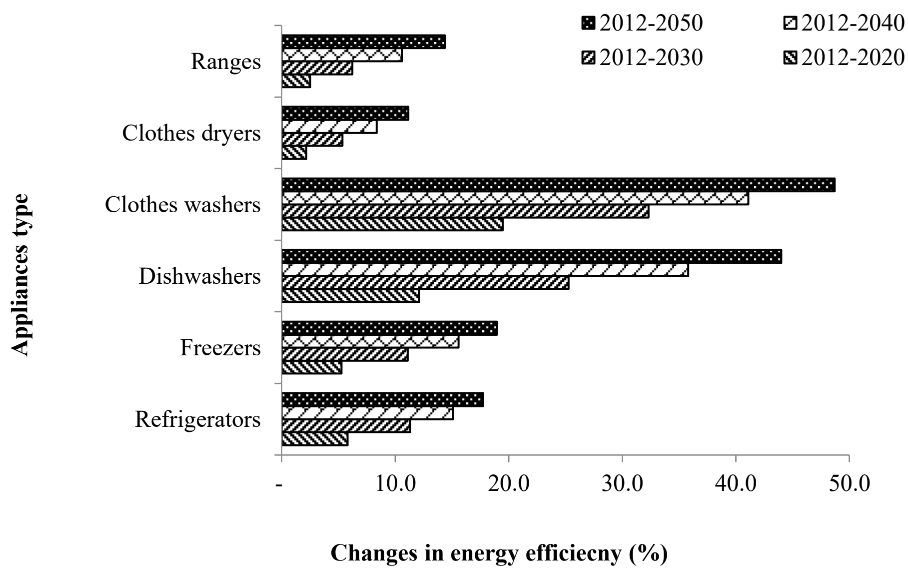


Figure 3-10: Accumulative changes in appliance energy efficiency by decade

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.

3.4.4. 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 3-11.

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.

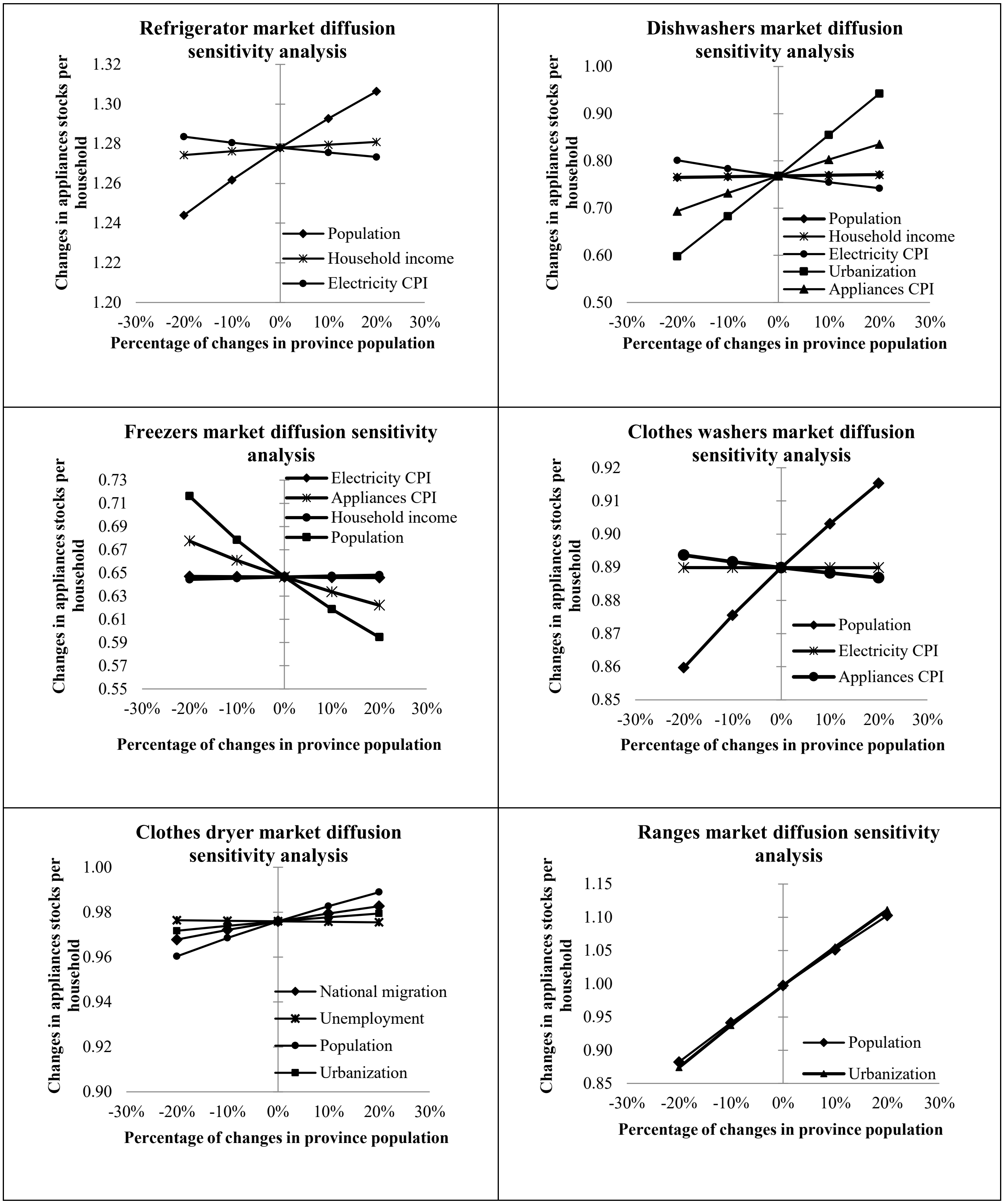


Figure 3-11: Sensitivity analysis results of developed penetration models

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 [154]. 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.

3.5. 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.

Chapter 4 : A New Market Penetration Modelling Framework for Novel in Situ Bitumen Extraction Technologies[5]

4.1. Introduction

The global community is facing pressing challenges to limit the average temperature to 1.5 °C above pre-industrial levels, which requires a net zero of human-caused greenhouse gas (GHG) emissions by 2050 [216]. Achieving such an ambiguous GHG reduction target would demand large-scale transformation in how energy is produced and consumed [217]. The global energy supplying system accounts for 35% of anthropogenic GHG emissions, mainly driven by increasing energy demand through rapid population and economic growth [218]. The oil and gas industry contributes significantly to energy suppling system emissions [219]. Around 5-10% of global fossil-fuel based GHG emissions are associated with oil and gas extraction and distribution processes [218]. Innovation in energy-efficient extraction technologies, the use of less carbon-intensive energy sources in upstream processes, and carbon capture and use are among the alternative pathways to reduce GHG emissions from the sector [218].

[5] A version of this paper was published in Energy journal - Radpour, S., Gemechu, E., Ahiduzzaman, M., Kumar, A. Development of a framework for the assessment of the market penetration of novel in situ bitumen extraction technologies. *Energy*, 220, 2021, 119666.

Canada is among the top global oil and gas producers [220]. The oil and gas industry plays a vital role in Canada's economy; it contributed more than 6% of the country's gross domestic product in 2018, largely from oil sands activities [221]. Production is forecast to increase by over 50% between 2018 and 2050, showing the significance of the sub-sector in Canada's economic future [222]. The oil and gas sector is also a major contributor of Canada's GHG emissions [223]. In 2018, the sector produced 197 Mt of CO_2 eq. (27% of the national emissions) [224]. Most of the emissions are associated with increased bitumen production, specifically from in situ extraction process [224]. Oil sands development alone accounted for 82 Mt of CO_2 eq. in 2018 [225]. With Canada's international and national climate change commitments, the oil sands industry is facing a huge challenge. Under the Paris Agreement, Canada committed to cut its emissions to 511 Mt of CO_2 eq. in 2030, 30% lower than the 2005 level [226]. Recently, the Government of Canada proposed a more ambitious climate change target of net zero emissions by 2050 under The Canadian Net-Zero Emissions Accountability Act [227]. The Act will set a science-based, credible national emissions reduction target every five years [227]. With respect to the oil sands industry, the Province of Alberta set a GHG emissions cap of 100 Mt of CO_2 eq. per year [228]. With all of these targets, the oil sands industry requires significant changes to reduce its environmental footprint and contribute to Canada's climate change commitment. There are several pathways to decarbonize the oil sands sector: energy management, upgraded control systems, and optimizing existing commercial recovery technologies.

The largest portion of GHG emissions from the oil sands industry comes from upstream processes. Extracting bitumen, which is highly viscous at reservoir conditions, requires more energy than producing oil from conventional resources [229]. Depending on how deep the oil sands are deposited, bitumen is extracted either using in situ or surface mining processes [230]. Crude bitumen from shallow mines is extracted via surface mining, which accounts for 46% of the total extraction [231]. In situ mining is used to recover bitumen located in deeper oil sands mines [232]. Cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD) are the two conventional in situ bitumen extraction methods. CSS uses a single wellbore for steam injection and oil production, and SAGD operates continuously by injecting steam through one wellbore and collecting the produced bitumen from another. Naphtha or natural gas-based diluent is added to reduce the viscosity of the produced bitumen so that it can be easily transported by pipeline and later recovered from bitumen. In an effort to reduce the GHG footprints of bitumen extraction, new technologies have been developed. Solvent-based extraction (SBE) and electromagnetic heating-based extraction (EHBE) are the two emerging technologies with greater energy efficiency than conventional extraction methods [233]. SBE use solvents such as propane instead of steam and operate at a lower temperature (40-45 °C) [234], which in turn reduces the energy and water requirements. A solvent vapor is injected into the reservoir to dilute and lift the bitumen to the production wells. SBE improves the overall bitumen production process because it leaves heavy components such as asphaltene inside the reservoir [235]. However, reducing the high (about 5) solvent-to-oil ratio is one of the challenges in SBE processes [236]. EHBE has similar well configurations similar to SAGD [237], but an antenna is needed in the upper well to heat the bitumen to 80 °C to accelerate the solvent diffusion rate [238]. The solvent is injected through the injector well to the reservoir and bitumen is drained to the production well. Because the solvents in EHBE are not the heating agent [239], the solvent-to-oil ratio is lower than in SBE [240].

The improvement in the sectoral emission intensity is due to the advancement of energy efficient technology and its wide deployment. However, additional energy and emission improvement measures such as the use of renewable energy, cogeneration, and carbon capture and storage can further increase the mitigation potential without major changes in the total bitumen production driven by Alberta's heavy oil price and new capital investments [241].

Although there are advancements in new technology development in the oil sands sector, it is important to study the wide deployment of those technologies and their GHG emission implications over the long term. Current research on emerging extraction technologies mainly focuses on understanding their environmental sustainability and techno-economic feasibilities. These include assessing the cost of SAGD [242] and upgrading processes [243], performance improvement [244], solvent-based extraction life cycle assessment [245] and process simulation [246], and electromagnetic heating-based extraction energy and GHG footprints [237]. However, little effort has been made to investigate the effects of technical and economic parameters on the market penetration and market shares of emerging oil sands extraction technologies and their GHG mitigation potential, energy savings, and energy intensity improvement. Market penetration is a measure of the sale of a product in a given market; this measure can help understand how a technology is adopted. Market share results from market penetration build-up over time for a specific technology. McKellar et al. investigated expected trends in oil sands GHG emissions using information from thirteen experts and concluded that incremental process changes will do little to reduce the intensity of GHG emissions; instead, technology availability and more stringent GHG mitigation policies are required to reduce emission intensities [247]. Sleep et al. ran an expert elicitation analysis and concluded that only small GHG mitigation potential is accessible with current regulatory conditions by 2034; they also forecasted the growth of market share for solvent-based processes in current conditions [248]. Both of these studies [32, 33] are based on expert opinions and survey sampling methods, and their results are mostly qualitative and useful only for short-term forecasts [34]. More recently, Janzen et al. analyzed the GHG mitigation potentials of the oil sands sector through carbon capture and storage [249], cogeneration [250], and the use of renewables and low-carbon energy technologies [251]. The results show that the oil sands sector can mitigate a maximum 7% of the cumulative GHG emissions between 2020 and 2050 through a carbon pricing policy [249], 2% through cogeneration [250], and 3.7% through renewable and low carbon technologies [251]. However, the GHG mitigation potential of emerging extraction technologies was not included in the assessments. Katta et al. evaluated the energy demand-based GHG mitigation potential of the oil sands sector and found it to be 7.6 Mt [223]. Although not for the oil sands sector, the study from the Energy Information Association used a market penetration model for energy systems to estimate energy use in 15 manufacturing and 6 non-manufacturing industries in several states in the United States [252]. The model uses detailed process flows and end-use accounting procedures. Market penetration was calculated based on the payback period and assuming linear changes in annual capacity additions over a 20-year period. However, the model does not capture the effects of changes in carbon price and oil price on the market [252]. Moreover, oil price varies according to a number of factors globally and can be forecast based on these factors. For example, Karasu et al. developed a model to forecast crude oil price to analyze the nonlinear properties of it with high precision [253]. While there are several attempts in research on market penetration in general, and the oil sands sector in particular, they are either limited to qualitative analyses or do not consider the potential impacts of economic measures such as carbon price. To the best of the authors' knowledge, there is not a single study that considers the long-term impacts of emerging extraction technologies on the GHG potential of the oil sands sector. In this context, the main purpose of this research is to address the literature gaps by developing a comprehensive market penetration and market share framework to determine the wide deployment of new technologies in the oil sands sector. The framework analyzes the effects of major parameters such as changes in Alberta's heavy oil price, carbon price, and economic factors on bitumen production, and consequently on the adoption of new energy technologies. The framework combines diffusion models, econometrics models, cost models, and energy-economy equilibrium models. A similar approach was developed by the authors in an earlier study to assess the market penetration of energy efficient technologies in the residential sector [254]. The specific objectives of this paper are:

- To develop a comprehensive framework to assess the market penetration and market shares of commercial and emerging energy efficient technologies in oil sands mining,
- To assess energy efficiency improvement opportunities in Alberta's oil sands mining sub-sectors,
- To assess the impact of carbon price on the market penetration of new technologies in Alberta's oil sands mining sector for the period 2018-2050,
- To assess the impacts of the carbon price and energy efficiency improvement on annual and accumulative GHG mitigation, and
- To assess the implications of carbon price in helping the oil sands sector to meet its climate change commitments.

4.2. Method

4.2.1. General framework

Fig. 1 presents the general framework of the MArket Penetration ModeL for Oil sands Extraction Technology (hereafter referred to as MAPL-OET) developed in this study. The framework integrates three main modules, namely, the total bitumen production module, the market penetration module, and the market share module. MAPL-OET allows us to extensively analyze the energy intensity and GHG mitigation potential of emerging bitumen extraction technologies in the oil sands sector over a long-time frame, in this case 2020 to 2050. The total bitumen market module uses macro-economic data at regional, national, and global levels and it employs several dynamic statistical analyses to determine total bitumen production under different carbon price scenarios. The carbon price scenario formulation is based on the current and probable future climate change policies in the federal and provincial governments [226]. The market penetration module evaluates the potential adoption of emerging bitumen extraction technologies due to the imposition of economic policy measures. Outputs from the market penetration modules along with bitumen production capacity addition/phase-out are used as inputs to the market share module to estimate the total production share of each extraction technology in different carbon price scenarios. The energy intensity and GHG mitigation potentials that result from the increased share of newer extraction technology are analyzed in detail. In the next section, each segment of the MAPL-OET framework is discussed.

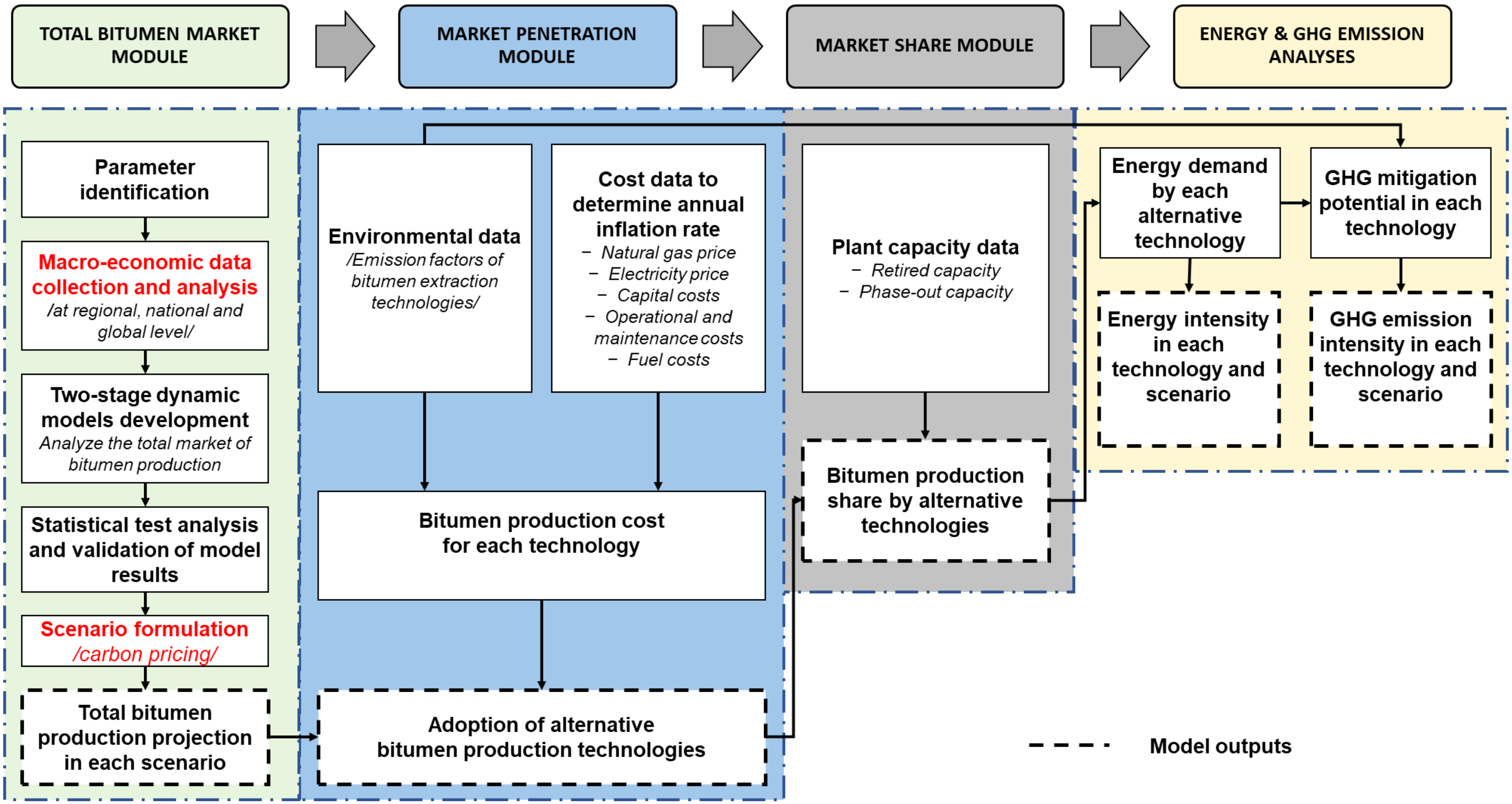


Figure 4-1: MArket Penetration ModeL for Oil sands Extraction Technology (MAPL-OET) framework

4.2.2. Total bitumen market module

Parameter identification and data gathering

This module involves a stepwise approach to project the total volume of bitumen production from 2020 to 2050. It starts with identifying the key parameters that could drive the demand and supply market of crude bitumen and data gathering. There are several factors that influence crude oil demand in general [255]. Global population and gross domestic product growth are two factors that affect energy demand [256]. Increase in demand for other fossil fuels and renewable resources, energy trade around the world, and energy demand of specific countries can also affect global crude oil demand [257]. The long-term outlook of Canadian crude bitumen is assumed to be affected by all of these factors. Particular to Alberta's bitumen production, studies on the historical trend and probable future use show that several economic factors affect investments in oil sands extraction development and bitumen production [231, 258]. Therefore, in order to identify the parameters most likely to induce change in bitumen production in Alberta, historical data on the following macro-economic information was gathered and analyzed: global population and of North America [259], natural gas and renewable energy production volumes [260], oil consumption in economically emerging countries such as China and India [260], energy demand in Asia and North America [259], global oil price [260], Alberta's heavy oil price [231], global natural gas price, crude oil price forecast for the years 2020 and 2030 [259, 261], and Canada's crude oil export to United States [231]. Detailed information on data gathered is provided in the supporting information (Table S-3 to S-9).

Statistical analyses

A statistical probability test using the least squares method was performed on the identified parameters to precisely determine their effect on total bitumen production. The least squares method is one of the standard approaches used in regression assessments working based on the minimum of residuals' squares value. To determine the effects of each parameter on bitumen production, Pearson's correlation was used as described in Eq. (4-1) [175]:

$$\boldsymbol{Ln(P_B) = a + b \times Ln(x)} \qquad \textbf{Eq. 4-1}$$

where P_B is bitumen production, x is the macro-economic parameter that potentially impacts bitumen production, and a and b are constant coefficients. The coefficients vary for each macro-economic parameter. The fittings in Eq. (4-1) were adjusted based on the conventional ordinary least squares (OLS) method using Eviews 8 SV statistical computing software [211]. Several statistical tests were also performed to analyze effective variables established in Eq. (4-1). Table 1 summarizes the tests considered.

The key parameters identified from the statistical test analyses were used to develop a two-stage dynamic modeling function, which is based on the Cobb-Douglas production function [176]. The general structure of the model is described in Eq. (4-2):

$$\boldsymbol{Ln(P_B) = a + b \times Ln(x_1) + c \times Ln(x_2) + d \times Ln(x_3)} \qquad \textbf{Eq. 4-2}$$

where x_1, x_2, and x_3 are variables that will be used in market penetration modeling and a, b, c, and d are constant coefficients.

Table 4-1: List of statistical tests to analyze effective variables in market penetration modeling

Prob.	It analyzes the probability of ineffectiveness of individual variables used in modeling. Values lower than 0.05 indicate that the related variable has a significant role in modeling [41].
R-squared (R^2) and *Adj. R-squared* (Adjusted R^2)	It analyzes the fitting degree of actual data by the developed model. The best value of these statistical tests in fitting is one. Adj. R-squared is useful to analyze the fitting degree when the amount of actual data is relatively high [41].
The *F-statistic* test	It analyzes the developed structure of the model by assuming that all the coefficients in the developed model (excluding the constant, or intercept) are equal to zero. Values lower than 0.05 are accepted [41].
The Durbin-Watson (DW)	It detects the serial correlation among the residuals [41]: $$\mathrm{DW} = \frac{\sum_{i=2}^{N}\left(\hat{\varepsilon}_i - \hat{\varepsilon}_{i-1}\right)^2}{\sum_{i=1}^{N}\hat{\varepsilon}_i^2}$$ ε is the residual value in each point. The residual value is the difference between actual data and modeled results at each point. DW values below 1.0 are evidence of positive serial correlation [41].

All the developed econometric models were analyzed based on the statistical tests as explained in Table 1. The model outputs were analyzed and validated using historical data. In validation process, the outputs from the developed models were compared with real historical data of total bitumen production in in situ and surface mining over several years and the average absolute percentage error was calculated.

Scenario formulation

Four carbon pricing scenarios were developed to analyze the market penetration and market share of bitumen-producing technologies: no carbon price scenario, low carbon price scenario, business-as-usual (BAU) carbon price scenario, and high carbon price scenario. Carbon pricing scenarios were formulated to capture the effects of a wide range of carbon price changes, from zero to \$105.52 per tonne of CO_2 eq., on market penetration, market share, energy saving, GHG emissions, and energy intensity improvement. The four scenarios are summarized in Table 2.

Table 4-2: Formulated carbon pricing scenarios from 2018 to 2050 for Alberta

Scenarios	**Description**
Zero carbon price	This is the condition in which no carbon price is imposed over the time period.
Business-as-usual (BAU)	The price of carbon is \$15 per tonne of CO_2 eq. and remains constant from 2020-2050.
Low carbon price	The price of carbon is \$30 per tonne of CO_2 eq. and remains constant from 2020-2050.
High carbon price	The price of carbon is \$30 per tonne of CO_2 eq. in 2020 and assumed to have an annual growth rate of 4%. The carbon price reaches \$ 105.2 per tonne of CO_2 eq. by 2050.

4.2.3. Market penetration module

In the market penetration module, the adoption rate of alternative bitumen extraction technologies is calculated based on the information from the total bitumen market module and the cost of bitumen production using alternative technologies. The market penetration module uses two-stage dynamic econometric models to calculate the contribution of in situ and surface mining on the total bitumen market. Input variables such as capital costs, operating costs, inflation rates, rate of capacity retirement, and improvement in emission factors of related technologies were calculated and used in the model. The model outputs were analyzed based on the list of statistical tests described in Table 1 and validated using historical data on the key parameters.

Econometric modelling has been widely used in various fields of study to estimate and analyze supply and demand at different economic levels [262-266]. Econometric modelling provides analyses from a systems-level perspective based on a conceptual relationship between dependent and independent variables [267]. The mathematical equations generated from an econometric model need to be analyzed using statistical tests before being used in the market share module [178].

4.2.4. Market share module

The market share module calculates the bitumen production shares by considering different extraction technologies using capacity replacement function. These models are functions of technology adoption by industry. Eq. (4-3) presents the market share model, which is based on the modified CIMS function [180, 268].

$$MS_j = \frac{(CC_j \times \frac{r}{1-(1+r)^{-n}} + OC_j + EC_j + Ct_j)^{-v}}{\sum_{k=1}^{K}(CC_j \times \frac{r}{1-(1+r)^{-n}} + OC_j + EC_j + Ct_j)^{-v}}$$ **Eq. 4-3**

MS_j is the market share of bitumen extraction technology *j (*cyclic steam stimulation, steam assisted gravity drainage, solvent-based extraction, and electromagnetic heating-based extraction).

Ct_j is the carbon price on technology *j*. The Alberta Government limits the GHG emissions from the oil sands industry and adds a carbon price as an economic incentive to make it more innovative and globally competitive while improving its environmental performance. We studied the impacts of carbon price on the market penetration of environmentally friendly emerging technologies by developing a market share module for alternate bitumen extraction and upgrading technologies. This will help to assess how carbon pricing policies help the industry meet CO_2 emissions reduction targets.

CC_j and OCj are the capital, and maintenance and operational costs excluding fuel cost of technology *j*. EC_j is the cost of energy used by technology *j*. *v* is the measure of the market heterogeneity and *r* is the discount rate. The market heterogeneity measure is a concept used to express non-uniformity in the system.

The market share evaluation based on Eq. (4-3) helps analyze the effects of changes in fuel pricing and carbon price set by the government or energy supplying organizations on the market share of a particular bitumen producing technology. The capital costs, operational and maintenance costs, energy intensities, and GHG emission intensities for each extraction technology are presented in Table 3.

Table 4-3: Cost, energy demand, and GHG emissions data

Bitumen production technologies	Capital costs ($/m^3 bitumen)	Operation & maintenance costs ($/m^3 bitumen)	Energy intensity (MJ/m^3 bitumen)	GHG emissions intensity (tonne of CO_2 eq./m^3 bitumen)
Steam assisted gravity drainage [229]	59.8	72.3	12914.1	0.90
Cyclic steam stimulation [229]	65.7	79.8	14851.3	1.04
Solvent-based extraction [245]	53.8	47.0	1139.9	0.19
Electromagnetic heating-based extraction [237]	50.3	62.3	2915.6	0.39
Upgrading (delayed coker upgrading)	96.4	55.8	3720.0	0.21

4.3. Results and discussion

This section presents and discusses output results from the three integrated modules in their corresponding sub-sections: total bitumen market, market penetration and market share modules.

4.3.1. Total bitumen market module results

The results from the total bitumen market module include the statistical analysis to screen the key parameters with high impact on total bitumen production and two-stage dynamic econometric modelling to forecast future bitumen production. The module involves analyzing 12 parameters, using 2 input variables, and solving 120 equations based on 4 econometric models. In the following sections the results from the statistical analyses, model validation, and effects of Alberta's heavy oil price on bitumen production are presented.

Statistical analyses results

The statistical analyses based on Eq. (4-1) and probability tests in Table 1 suggest that Alberta's heavy oil price is the parameter that most influences total bitumen production. This is explained by the Prob. values being close to zero, the highest R-squared and Adj R-Squared values (0.97 and 0.96, respectively), and the highest Durbin-Watson statistical tests of all other parameters. Detailed results from statistical and probability tests are presented in the support information (Table S-1). Total bitumen production from in situ and surface mining processes was estimated using the two-stage dynamic econometrics mathematical models and historical data on Alberta's heavy oil price and new capital investment from 1997 to 2016. The new capital investment was used as an intermediate variable that connects oil price and bitumen production. A summary of the key results is presented in Table 4.

Table 5 presents the statistical test results from the two-stage dynamic models (shown in Table 4). The Adj. R-squared values for new capital investment and bitumen production in surface mining and in situ mining are close to one. This suggests that the models can predict the changes in actual data accurately. The Prob. values in most cases are less than 0.1 (less than 0.05 for some variables). Moreover, the Prob. F statistic is zero in all four cases. The Durbin-Watson statistic values are greater than 1, which indicates a very low probability of serial correlation in the developed models. The statistical test results highlight the validity of the developed models in estimating bitumen production from in situ and surface mining.

Table 4-4: Two-stage dynamic econometrics models developed to analyze bitumen-producing technologies

$ln\ (NCI_{surf}\ (t)) = -0.9605 + 0.2957 \times ln\ (p(t-1)) + 0.6674 \times ln(NCI_{surf}(t-1))$	**Eq. 4-4**
$ln(P_{B\_surf}(t)) = 1.3859 + 0.1369 \times ln\ (NCI_{surf}(t-1)) + 0.6673 \times ln(P_{B\_surf}(t-1))$	**Eq. 4-5**
$ln(NCI_{insitu}) = -5.3385 + 1.0841 \times ln(p(t-1)) + 0.5088 \times ln(NCI_{insitu}(t-1))$	**Eq. 4-6**
$ln(P_{B\_insitu}) = -0.0583 + 0.0095 \times ln(NCI_{insitu}(t-2)) + 1.0320 \times ln(P_{B\_insitu}(t-1))$	**Eq. 4-7**

Where:

p (t) is Alberta's heavy oil price in year *t*, P_{B_insitu} *(t)* is bitumen production by in situ mining in year *t*, P_{B_surf} *(t)* is bitumen production by surface mining in year *t*, NCI_{insitu} *(t)* is new capital investment in in situ mining in year *t*, and NCI_{surf} *(t)* is new capital investment in surface mining in year *t*.

Table 4-5: Modeling statistical test results, probability analysis results, and Durbin-Watson statistics

	Adj. R-squared	Prob. (a)	Prob. (b)	Prob. (c)	Prob. F statistic	Durbin-Watson statistic
NCI_{surf}	0.981	0.043	0.026	0.001	0.000	2.215
NCI_{insitu}	0.999	0.005	0.004	0.003	0.000	1.489
P_{B_surf}	0.928	0.023	0.060	0.003	0.000	2.591
P_{B_insitu}	0.989	0.033	0.045	0.000	0.000	1.562

Model validation

The accuracy of the bitumen production module was validated by comparing the model results with historic and forecast data as shown in Fig. 2 and Fig. 3. The historical data on bitumen production is from the Alberta Energy Regulator (from 1998 to 2015) [269] and the forecast data is from the Canada Energy Regulator (from 2020 to 2040) [232]. The absolute average error percentages between the actual and historic data are 3.31% and 2.56% for surface mining and in situ mining, respectively. This shows that the developed models can accurately and effectively capture the changes in oil sands production. Similarly, the results from bitumen production are consistent with the forecast data from the Canada Energy Regulator (Fig. 2).

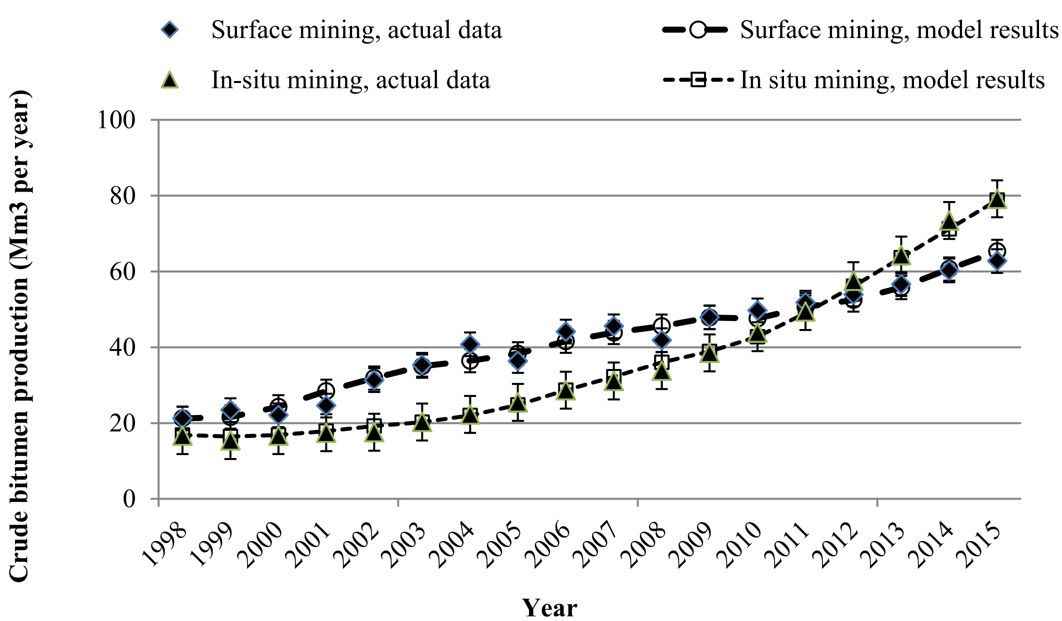


Figure 4-2: Comparison of total bitumen market module results with actual data for bitumen production by surface mining and in situ mining (1998-2015) [232]

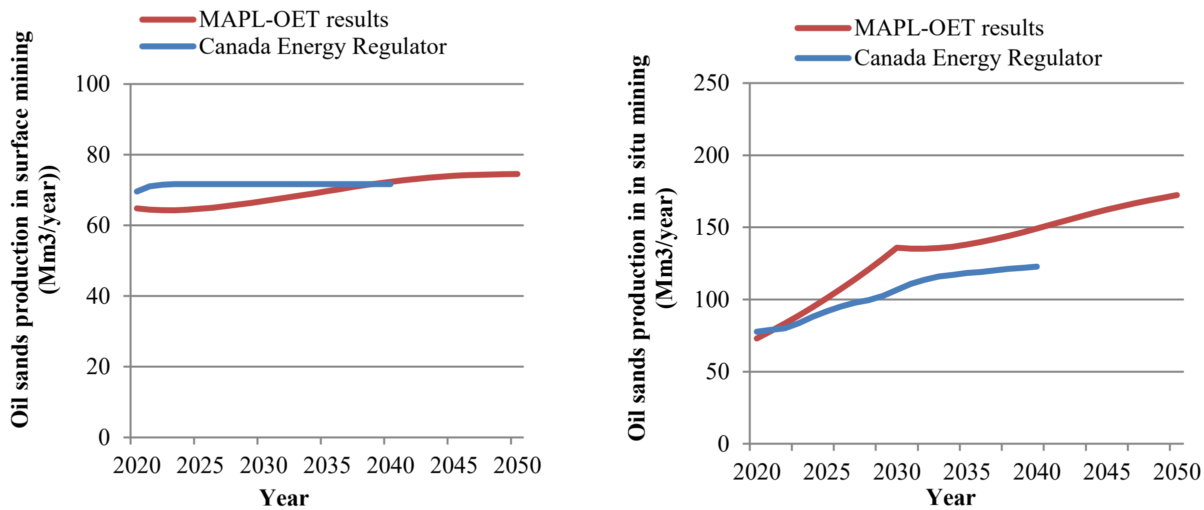


Figure 4-3: Oil sands production estimates in surface mining and in situ mining

Effects of Alberta's heavy oil prices on bitumen production

The sensitivity of bitumen production to Alberta's heavy oil price was analyzed considering a wide range of probable oil price annual growth rates of the price change. Based on historical and forecasted data from the Canada Energy Regulator, the following growth rates were assumed: 0.75%, 1%, and 1.75% [232]. However, the growth rate of Alberta's heavy oil price could be higher or lower depending on the trends of demands, technology improvements, geopolitical events, and implementation of GHG emission policies by other countries [232]. The results are presented in Figure 4. In situ mining's total bitumen production responds to changes in prices more than surface mining's total production. The average annual growths of bitumen production for in situ mining was 5.3% and 0.94% if Alberta's heavy oil price annual growth is 1.75 and 0.75, respectively. The annual growth rate for surface mining is 0.64% and 0.11% if Alberta's heavy oil price growth is 1.75 and 0.75, respectively. Historically, surface mining has contributed the largest share of oil sands development. However, over time, the oil sands deposits that are accessible through mining are diminishing and the future oil sand development is becoming dominated by in situ mining.

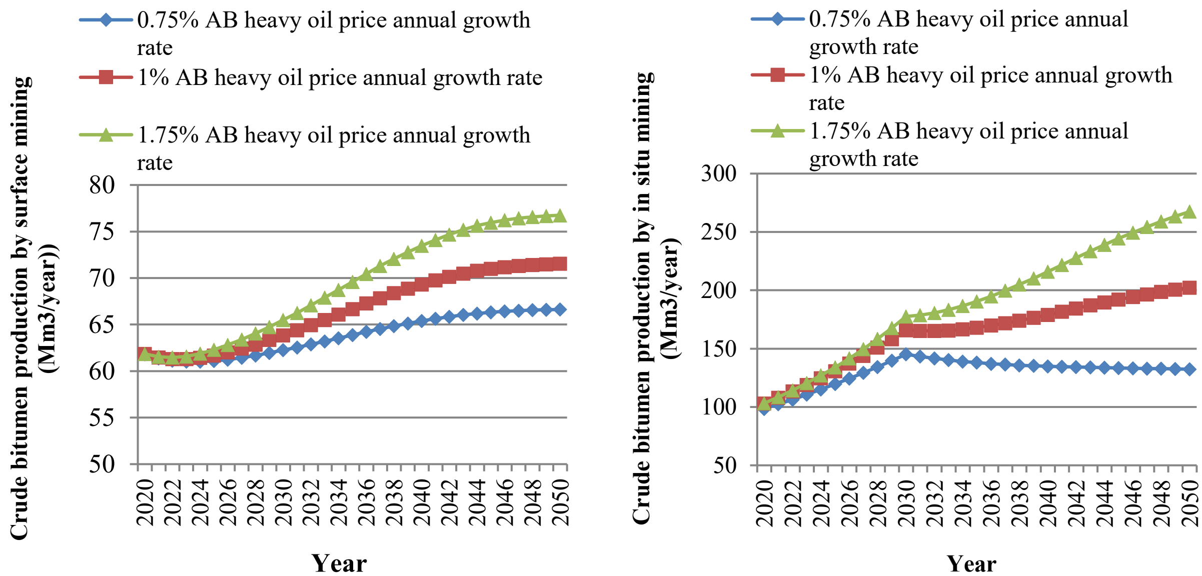


Figure 4-4: Crude bitumen production estimates in the low, reference case, and high scenarios in surface mining and in situ mining

4.3.2. Market penetration and market share modules results

The market penetration module forecasts the adoption of emerging bitumen extraction technologies using 12 variables and 600 dynamic integrated equations to calculate new added bitumen production capacity, annual bitumen production, energy demand, GHG emissions, and energy intensity improvements in four carbon pricing scenarios from 2020 to 2050. The market share results for each bitumen production technology are presented in Fig. 5.

A comparison of crude bitumen production in different carbon price scenarios shows that implementing a high carbon price can significantly facilitate the market penetration of more environmentally friendly technologies. The market shares of solvent-based extraction, which has a relatively lower GHG emission footprint and energy intensity, could be 75 Mm^3/year by 2050 in the high carbon price scenario; this is higher than the zero scenario (54 Mm^3/year), the BAU scenario (62 Mm^3/year), and the low carbon price scenario (69 Mm^3/year). Analysis of the market penetrations and market shares of different technologies shows that solvent-based extraction could penetrate faster than electromagnetic heating-based extraction. Market penetration ranges from 3.2% in the zero scenario (2020) to 34.1% in the high carbon price scenario (2050). EHBE also has a higher market penetration than conventional bitumen extraction technologies. The value ranges from 0% in the zero carbon scenario (2020) to 10.1% in the high carbon price scenario (2050). Compared to solvent-based extraction, EHBE has a lower performance. EHBE requires a high amount of electricity for the antenna; this could affect the cost of production as well as the GHG performance and associated carbon costs. The impacts of carbon pricing in energy and GHG emission intensive extraction technologies such as steam assisted gravity drainage are considerable. Steam assisted gravity drainage shows a decreasing trend of market share, from 55% in the zero scenario in 2020 to 33% in the high carbon price scenario in 2050. The developed models were able to capture the potential impacts of carbon price and Alberta's heavy oil price on total production and consequently on the market penetration of energy efficiency technologies.

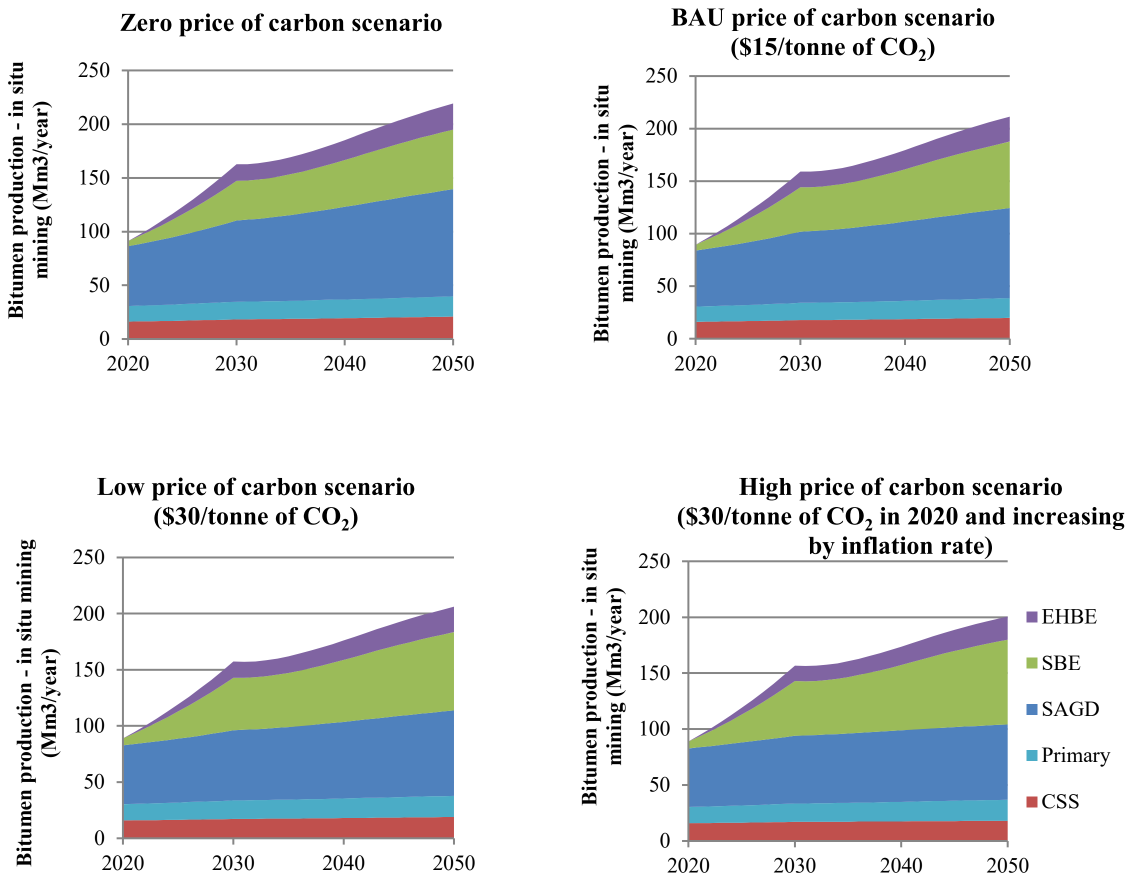


Figure 4-5: Crude bitumen production in in situ mining by major commercial and potential emerging technologies (2020-2050)

4.3.3. GHG emissions and energy analyses

The effects of bitumen extraction technologies on the long-term GHG mitigation potential of the oil sands industry are discussed in this section. The emissions are estimated based on the life cycle GHG intensity of each technology and total bitumen production projection results from the market penetration and market share models for all carbon price scenarios. The GHG emissions results are shown in Fig. 6. In addition to in situ mining, GHG emissions from surface mining are added in order to have a better understanding of the total emissions from the oil sands industry.

Although the share of less GHG-intensive extraction technologies is increasing, the overall emissions show a growing trend in all the scenarios. This can be explained by bitumen production growth, which outmatches improvements in the sector's GHG performance. The high carbon price scenario offers relatively lower GHG emissions. This is mainly due to the increasing share of less emission-intensive extraction technologies. The GHG mitigation potential of the sector through carbon pricing is compared with the 100 Mt of CO_2 eq. emissions cap. The high carbon pricing scenario can help the industry achieve 103.56 Mt of CO_2 eq. GHG emissions in the other scenarios are 125.4 Mt of CO_2 eq. (zero carbon price), 116.2 Mt of CO_2 eq. (BAU), and 109.8 Mt of CO_2 eq. (low carbon price).

With increasing energy demand due to economic and population growth, GHG emissions from the oil sands sector are projected to increase. However, the GHG intensity (the ratio of total emissions to total bitumen production) reduces from 0.76 to 0.51 tonnes of CO_2 eq./m^3 of bitumen production in the zero and high carbon price scenarios between 2020 and 2050. The improvement in the sectoral emission intensity is due to the advancement of energy efficient technology and its wide deployment. However, additional energy and emission improvement measures such as the use of renewable energy, cogeneration, and carbon capture and storage can further increase the GHG mitigation without major changes in the total bitumen production [241].

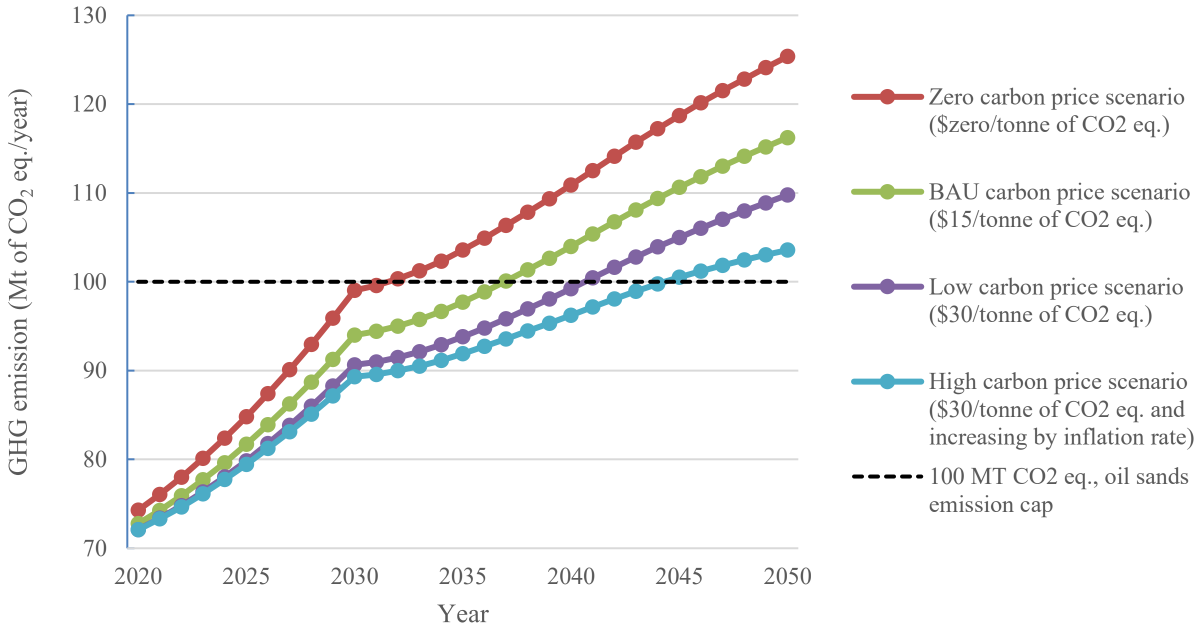


Figure 4-6: GHG emissions from crude bitumen production in different carbon pricing scenarios (2020-2050)

4.3.4. Energy demand and intensity analysis

Projecting the market penetration of energy technologies in the oil sands industry shows that although crude bitumen production will increase, energy intensity will decrease, largely due to new efficient technology penetration. In situ mining operations energy demand is shown in Fig. 7. Energy demand is calculated based on the energy intensity of each technology and is used to calculate the average energy intensity improvement as well.

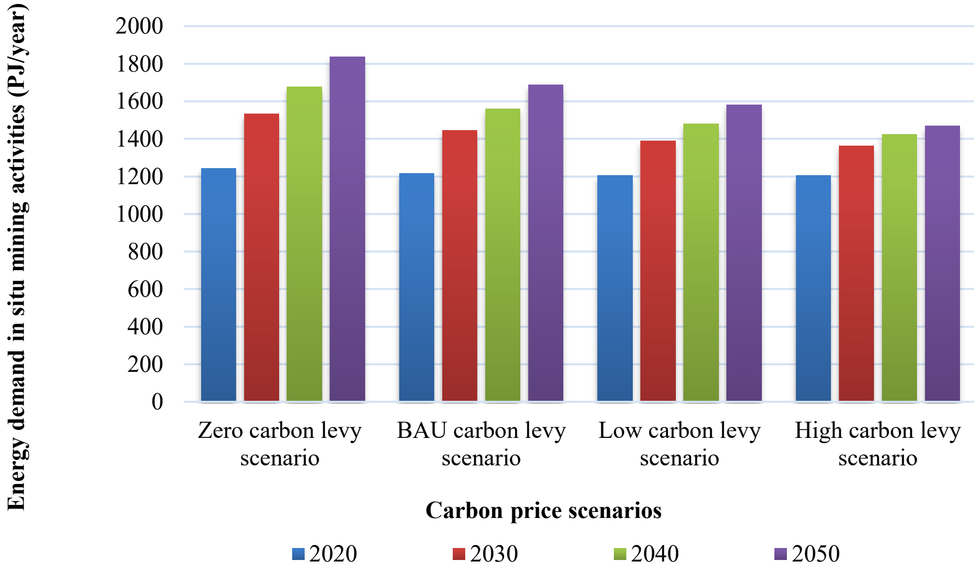


Figure 4-7: Energy demand of in situ mining activities in different carbon price scenarios in 2020, 2030, 2040, and 2050

Implementing carbon price scenarios is more effective in 2050 than in 2020 because of the higher market share of efficient technologies by the later date. Energy intensity in terms of energy demand per unit of crude bitumen production was analyzed for the different carbon price scenarios. As shown in Figure 8, there is a high potential to improve energy efficiency by decreasing energy intensity in in situ oil sands production. The high carbon price scenario offers the largest average annual decline rate of energy intensity (-1.31%) than other scenarios. The low carbon price, BAU, and zero carbon price scenarios result in energy intensities of -1.20%, -1.01%, and -0.94%, respectively.

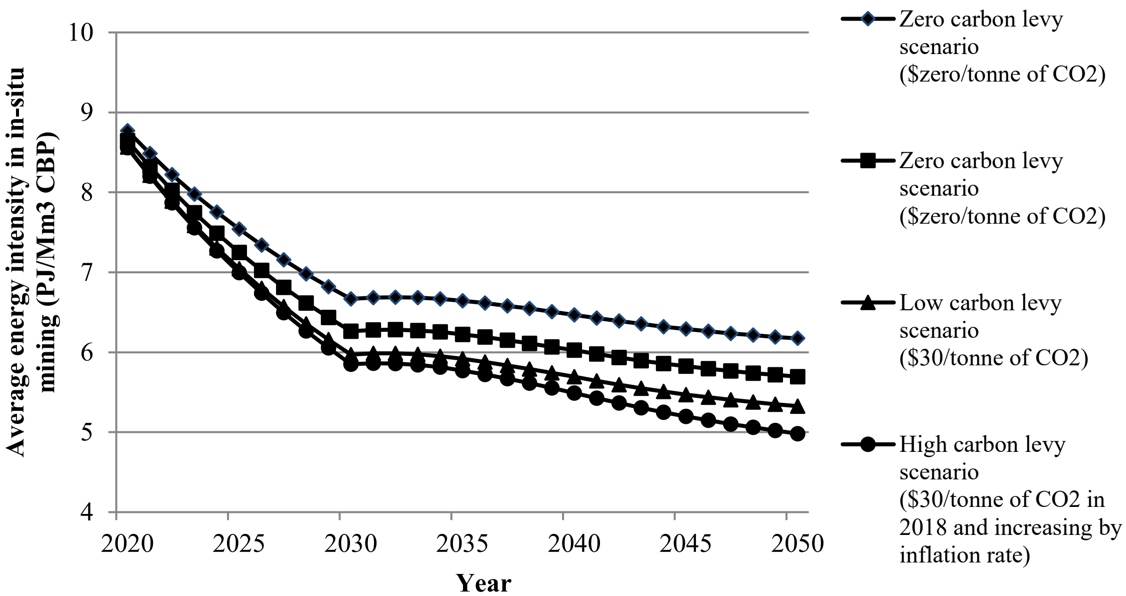


Figure 4-8: Energy intensity improvement in in situ crude bitumen production (2016-2050)

The MAPL-OET framework was developed for the oil sands sector in Alberta; however, it can also be used for other energy technologies or industries. Depending on the technological specification and energy characteristics, the input requirements and the model formulation may need adjustments. For example, the total bitumen market module evaluates the key parameters that affect the production in the long-term using macro-economic information and sets of statistical analyses, which are specific to the oil sands industry. The other important aspect is the scenario formulation. In this paper, the focus is to see the impact of carbon price on the adoption of new extraction technology. Different scenario formulations could also result in different model outputs. Therefore, it is important to take those aspects into consideration when interpreting the results and discussion in this paper.

The framework is data-intensive, which requires gathering historical data at different economic levels, collecting environmental and techno-economic information, and considering commercialization time of new technologies. The data is sometimes difficult to obtain because of the low technology readiness level of the emerging technologies and associated uncertainties that can affect the output results.

It is also worth mentioning that, in its current form, the MAPL-OET framework does not analyze the impact of geopolitical and unpredicted environmental and economic factors that could affect the global oil market, as they are beyond the scope the paper.

4.4. Conclusion

With increased focus on greenhouse gas (GHG) mitigation, the oil and gas sector is looking for ways to reduce its GHG emissions while remaining competitive. In Canada, the oil and gas sector is one of the major GHG contributors. A significant share of emissions is due to oil sands production. With Canada's focus on reducing GHG emissions, there is a focus reducing GHG emissions in the oil sands sector. There are developments in energy-efficient extraction technologies such as solvent-based extraction and electro-magnetic heating-based extraction to reduce energy and GHG emission intensities of the sector. While there is ongoing research on emerging technologies, there has been limited focus on understanding the long-term impacts of those technologies on the GHG mitigation potential of the sector. Understanding the future adoption and wide deployment of emerging extraction technologies by developing a comprehensive market penetration and market share framework is the knowledge gap addressed in this research.

The main objective of this paper is to develop a novel and comprehensive market penetration and market share framework called MAPL-OET to analyze how changes in Alberta's heavy oil price, carbon price, and economic factors affect total bitumen production from 2020 to 2050. The framework also evaluates the adoption of new energy technologies as a result of carbon price measure and also the GHG mitigation potential of the oil sands sector. Based on the model results, Alberta's heavy oil price and new capital investment are the factors that most affect bitumen production. The model projection results suggest that the implementation of a high carbon price in the oil sands industry can facilitate the market penetration and market shares of environmentally friendly technologies. The adoption of new technologies motivated by the carbon price policies can reduce GHG emissions in the oil sands sector to a maximum 103.56 Mt of CO_2 eq. in 2050 from 116.4 Mt of CO_2 eq. in the business-as-usual (BAU) scenario. The accumulated GHG mitigation potential between the high carbon and BAU scenarios were estimated to be 192.8 Mt of CO_2 eq from 2018 and 2050. The average energy intensities improved annually by -1.01% and -1.31% in the BAU and high carbon price scenarios, respectively.

The MAPL-OET framework can be used for energy technologies in other industrial sectors as well as other locations with adjustments in input data. In its current form, the MAPL-OET framework does not analyze the impact of geopolitical and unpredicted environmental and economic factors that could affect the global oil market.

The developed new framework can help decision makers analyze the market penetration of available technologies and retrofitting alternatives.

Chapter 5 : Market Penetration Modeling of Renewable Energy Technologies in Electricity Generation Sector[6]

5.1. Introduction

The global temperature increase needs to be limited to well below 2 $^{\circ}$C above pre-industrial levels in order to reduce the adverse effects of climate change [270, 271]. Greenhouse gas (GHG) emissions associated with human activities are the key driver of anthropogenic climate change impacts; two-thirds of the emissions are attributed to fossil fuel-based energy use [272]. The energy system requires an accelerated low-carbon transition to ensure significant reduction in energy supply and use related to GHG emissions while meeting the increasing demand driven by population and economic growths. To achieve the 2 ºC target set under the Paris Agreement, the CO_2 intensity of the global economy should be 85% lower than the intensity in 2015 by 2050 [273]. Innovation in energy efficient technologies including renewable sources and increasing the share of clean energy are among the critical pathways to ensure the transition [28, 31, 273, 274]. Since 1990, renewable energy has shown a remarkable growth, an average annual rate of 2%, which is higher than the annual rate of total energy supply [275]. However, the transition to increasing shares of renewable energy technology also poses technical, environmental, and socio-

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[6] A version of this paper was submitted to Renewable and Sustainable Energy Reviews journal - Radpour, S., Gemechu, E., Ahiduzzaman, M., Kumar, A. Developing a framework to assess the long-term adoption of renewable energy technologies in the electric power sector: the effects of carbon price and economic incentives. 2020 (in review)

economic challenges [276-279]. Those aspects need to be factored to better understand the market penetration potential of emerging renewable energy technologies for a particular jurisdiction, which is the purpose of this paper.

Canada is among the top ten global GHG emitters, responsible for 728 Mt CO_2 eq. in 2018 [280]. As a response to international climate change commitments, under the Pan-Canadian Framework on Clean Growth and Climate Change, the country targeted to reduce its GHG emissions to 511 Mt CO_2 eq. by 2030, 30% lower than the level in 2005 [226]. Canada also recently proposed a new climate change target of net-zero emissions by 2050 [227]. A series of actions is required to achieve those targets. Renewable energy technologies have a significant role in Canada's pathway to net-zero emissions. The country has considerable renewable energy sources: biomass, geothermal, hydropower, ocean resources, solar, and wind [281]. Wind and solar photovoltaic generated 5.2% and 0.5% of Canada's electric power in 2017, respectively, and are expected to grow faster than other renewable resources generating electric power in the coming years [280]. If coal, a non-renewable source of electric power, is scheduled to be fully phased out by 2030, other non-renewable and renewable electric power resources can fill the anticipated gap in the market. Canada's transition to a low-carbon economy and clean energy technology requires significant investment in renewable energy resources and efficient electricity generation technologies in order to increase market penetration while maintaining the competitiveness of the resources and technologies [31, 274]. The high initial capital cost, lack of financial investors, the place of fossil fuels in the current energy system, and fewer incentives than for traditional fuels are among the economic challenges that should be addressed [42]. Incentives and implementing a carbon price could promote the use of renewable energy and hence its market penetration [282]. Hence, in this paper, we aim to develop a market share and penetration modelling framework to systematically answer the overarching research questions: what are the key drivers in the total electricity demand in the long run? What effect do key technical and economic factors have on the widespread use of renewable energy technologies in the power sector? What is the GHG mitigation potential of renewable adoption in the long term?

The market penetration of renewable energies has been widely studies in the literature. Some studies use experience/learning curves to investigate, for instance, the potential cost of GHG emissions reduction through economies of scale following improved market penetration [50-54]. Learning curves are based on the reduced cost of new technologies and changes in output during the cost reduction period [55, 56]. The economic viability of renewable energy technologies compared to available alternatives has also been studied [57-60], and the results show that many factors affect the market penetration of renewable energy technologies in the electric power generation sector, including techno-economic factors, system infrastructure characteristics, and institutional factors such as provincial, national, local, and global protocols and conventions [26, 57]. The effects of government policies on renewable energy technologies' adoption have been studied through a system dynamics approach [58] and diffusion models [55, 56, 58]. Most studies analyzed a specific renewable energy source such as wind or solar [57, 283, 284]. However, few market penetration studies consider technical and economic factors, which are critical when developing energy system models for market penetration and market shares of different technologies on the supply side, as are carbon price and governmental policies [285, 286]. The United States National Energy Modeling System used a market penetration model for energy systems to estimate energy use in the industry sector [252]. This model is based on end-use accounting procedures and calculates the rate of market adoption by using the payback period and assuming linear changes in capacity additions over a 20-year period. However, the model does not analyze changes in carbon price and financial incentives on the market penetration of energy technologies [252].

None of these studies focusses on the integration of carbon pricing scenarios or financial incentives on the market penetration of renewable energy technologies. The developed framework in this research, therefore, incorporates these aspects in a new market penetration model for renewable energy in the electric power generation sector and addresses the literature and knowledge gaps. Although there are several studies on the market penetration of renewable technologies, the integrated quantitative impacts of three parameters (carbon pricing scenarios, financial incentives, and phasing out coal-based power plants over a particular timeline) have not been investigated. To the best knowledge of the authors' knowledge, there is no study that analyzes the long-term impacts of these three factors on the market penetration of renewable technologies in the electricity supply sector. The developed MArket Penetration ModeLling of Renewable Energy Technologies in Power Sector, or MAPL-RET, is a comprehensive, data-intensive, dynamic model that combines econometric functions, market share models, and trend analysis based on technical and economic factors and planned replacements in the electric power supply side over time in dynamic models. This framework allows us to improve model reliability and to analyze the effects of changes in several aspects of the market penetration of electric power generation technologies. A case study on Alberta's electric power sector with a focus on large-scale electric power generation for the years 2020 to 2050 was modeled by using MAPL-RET. In this case study, we quantitatively analyzed the effects of carbon pricing, financial incentives, and the phasing out of coal-based power plants from 2020 to 2050, and we also considered whether these three parameters can reduce GHG emissions by 2050 to 20% below Alberta's electric power sector's 2020 emissions. Moreover, we assessed whether these three parameters can increase the share of renewable energies from 12.5% in 2018 to 30% in 2050. The model can be used in other regions with some adjustments in input data such as energy carrier price, carbon price, capital and operating costs, macroeconomic parameters such as GDP and population, and local government policies on electric power technologies. The specific objectives of this paper are:

- To develop a comprehensive framework to assess the market penetration and market shares of renewable energies in the electric power supply sector;
- To assess the electric power demand based on the time series of economic factors such as GDP, electricity price, and population;
- To analyze the impacts of economic incentives on total electricity demand and on the market penetration of low-carbon energy technologies in the electricity generation sector;
- To investigate the potential impacts of economic incentives on annual and accumulated GHG mitigation from the sector; and
- To assess the implications of carbon price in helping the electric power generation sector to meet its climate change commitments.

5.2. Method

5.2.1 General framework

Figure 5-1 presents the general framework for MArket Penetration ModeLling of Renewable Energy Technologies in Electric Power Sector, abbreviated MAPL-RET. It is a comprehensive and data-intensive framework that systematically evaluates the long-term effects of renewable energy technology adoption in the electricity grid mix and the associated GHG mitigation potential. The framework comprises three modules: the total electricity demand module, market penetration module, and market share module. The total electricity demand module determines the market volume of electricity. It involves macro-economic data gathering and performing statistical analysis to identify key factors that dictate the change in final electricity demand in a particular jurisdiction. The consequences of climate change policy measures in inducing change in the energy demand are assessed by developing carbon prices scenarios. The market penetration module analyzes the adoption of renewable energy technologies based on the output from the total electricity demand module and using the environmental and techno-economic performances of each electricity generating technology. The relative share of each technology in the total electricity demand in a given time is quantified using the market share module. In the following sections, each module is discussed in detail.

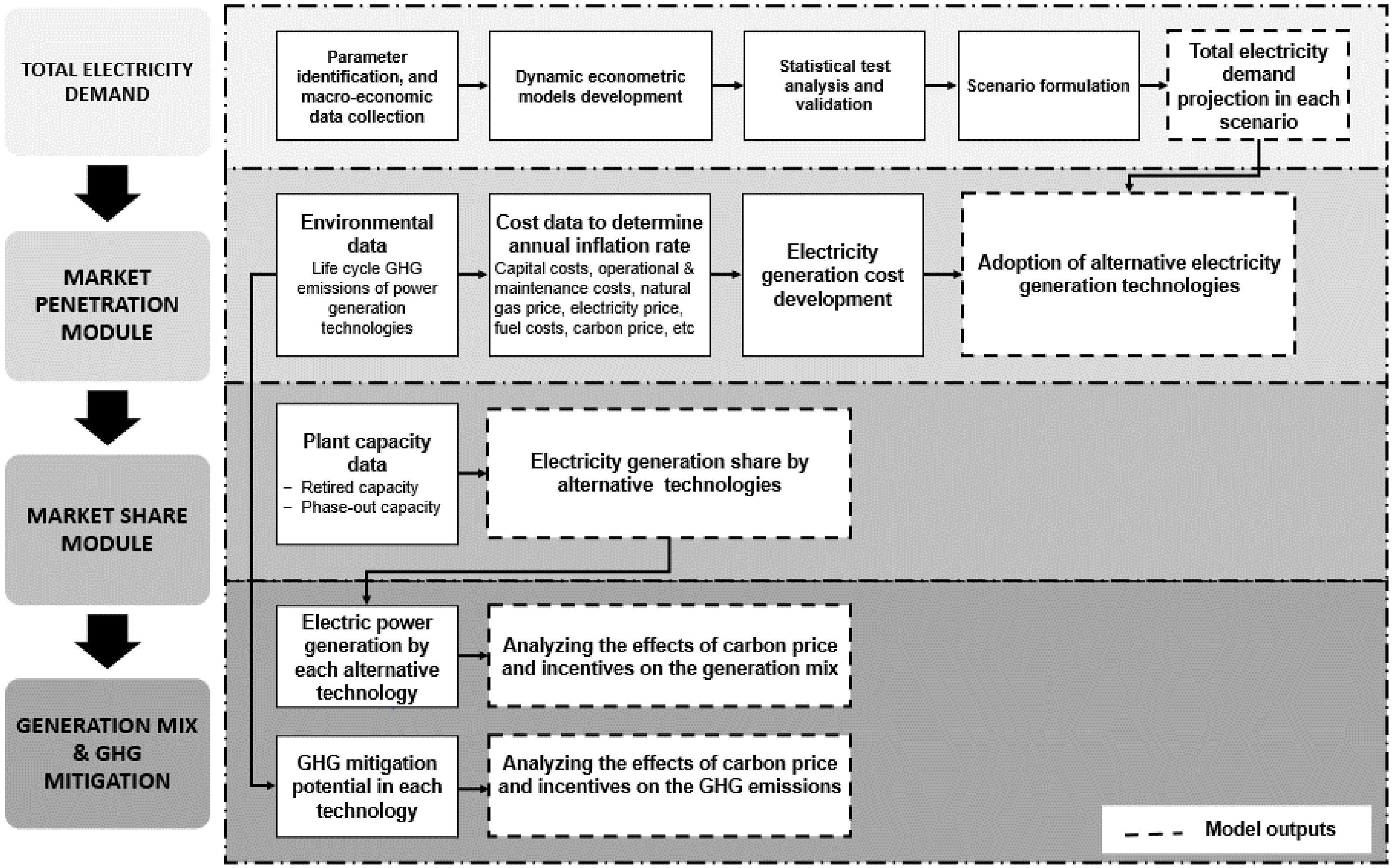

Figure 5-1: MArket Penetration ModeLling of Renewable Energy Technologies in Electric Power Sector (MAPL-RET) framework

5.2.2 Total electricity demand module

This part of the framework involves parameter identification, data gathering, statistical model development and analysis, and scenario formulation. Statistics Canada [287, 288], Natural Resources Canada [289], the International Energy Agency [280] are three main data sources consulted. A statistical test using the conventional ordinary least squares method was performed for this purpose. Electricity price, electricity share in total energy use, gross domestic production, natural gas price, natural gas share in total energy use, population, and gasoline price are the main parameters considered [178]. The ordinary least squares method is a standard procedure in statistical regression analysis. It is used to approximate the solution of overdetermined systems by minimizing the sum of the squares of the residuals in the results of every single equation. Pearson's correlation was used to measure the linear correlations between the parameters as described in Eq. (5-1) [290], where E is the total electricity demand, x is the macroeconomic variable affecting electricity demand, and a and b are constant coefficients in each model.

$$\boldsymbol{Ln(E) = a + b \times Ln(x)} \qquad \textbf{Eq. 5-1}$$

The fitting parameters were adjusted using the statistical computation software EViews 8 SV [211]. Table 5-1 summarizes the statistical tests implemented to analyze each variable.

The total electricity demand is modeled using econometric models based on the Cobb-Douglas production function [291]. The Cobb-Douglas production function is used to study the relationship between macroeconomic factors and electricity demand in a time series. The general structure of the model is described in Eq. (5-3) [177]:

$$\boldsymbol{Ln(E) = a + b \times Ln(x_1) + c \times Ln(x_2) + d \times Ln(x_3)} \qquad \textbf{Eq. 5-3}$$

where E is the total electricity demand, x_1, x_2, and x_3 are variables used in market penetration modeling, and a , b, c, and d are constant coefficients in each model. Production functions are used widely in different fields to estimate and analyze the supply and demand of a product system from a given sector, region, province, or country [204, 267]. The functions are based on the conceptual relation between dependent (e.g., total electricity demand) and independent variables (e.g., electricity price) [178]. The accuracy of the developed mathematical equations is analyzed through statistical tests before they are used in market penetration analysis [36, 292].

Table 5-1: List of statistical tests performed [211]

- Prob. determines the effectiveness of individual variables. Prob. values less than 0.05 indicate that the variable has an important role in the modeling
- R-squared (R^2) measures the degree data fitting in the developed model, the value 1 indicates best fitting.
- Adj. R-squared (Adjusted R^2) allows to analyze the fitting degree when the data volume is relatively high to ignore an increase in undesired R-squared.
- The prob. (F-stat.) test is used to analyze the validity of the model structure with the assumption that all the coefficients in the developed model (excluding the constant, or intercept) equal zero. Developed models with prob. (F-stat.) values lower than 0.05 pass the statistical test.
- The Durbin-Watson (DW) statistic test as described in Eq. (5-2) is used to detect the serial correlation among the residuals. ε is the residual value, a difference between actual data and modeled results at each point. High DW test values show low potential for positive serial correlation.

$$\mathrm{DW} = \frac{\sum_{i=2}^{N}\left(\hat{\varepsilon}_i - \hat{\varepsilon}_{i-1}\right)^2}{\sum_{i=1}^{N}\hat{\varepsilon}_i^2} \qquad \textbf{Eq. 5-2}$$

5.2.3 Market penetration and market share modules

The market penetration module determines the adoption rate of alternative electric power generation technologies based on the results from the total market analysis and the total cost of electricity generation from each technology. This module uses dynamic econometric models to calculate the contribution of alternative power generation technologies. The major variables used in this module are capital costs, operating and maintenance costs, inflation rates and capacity retirement rate. Moreover, carbon price along with associated emission factors for each technology and probable financial incentives are used to calculate the market adoption rate of each technology based on the energy-economy equilibrium model described by Bataille et al. and Nyboer [179, 180] (Eq. 5-4):

$$MS_j = \frac{\left(\llbracket CC_j \times \frac{r}{1-(1+r)^{-n}} + OC_j + EC_j + CL_j \right)\rrbracket^{-v}}{\sum_{k=1}^{K}\left(CC_j \times \frac{r}{1-(1+r)^{-n}} + OC_j + EC_j + CL_j\right)^{-v}} \quad \textbf{Eq. 5-4}$$

where MS_j is the market share adoption of technology j in a specific year, CC_j is the capital cost, OC_j is maintenance and operation costs, EC_j is the energy cost, CL_j is the carbon emission cost, r is the discount rate, v is the measure of market heterogeneity, and K is the number of competing technologies. Market adoption affects the added capacity by new installed capacity based on the overall new capacity and replaced retired capacity.

The market share of alternative electricity generating technology is calculated with the market penetration module output and technology adoption rates. The market adoption rate results, along with phase-out and retired capacities, were used to develop the accumulated technology replacement function and ultimately provide the market share of an individual technology in a specific time period. Carbon price and economic incentives scenarios were formulated to evaluate the potential impact of policy measures on the adoption rate of each technology based on their GHG emissions performances.

5.2.4 Alternative technologies in electric power generation

The framework is applied to Alberta electric generation, a fossil-dominated province in Western Canada. In Alberta, coal and natural gas are the two major sources of energy in the gird mix, contributing 51% and 39%, respectively in 2017 (82,572 GWh of the total electric power generation) [293]. Wind, biomass, and hydro together accounted for 10% of the generation [293]. The trend in Alberta's electric power generation by resource is presented in Table S5-1 [294]. Resource availability plays a significant role in electric power generation from renewables. The estimated potential for renewable energy resources in Alberta is provided in the supporting information (Table S5-2). The renewable energy resource potential is much higher than the current electric power generation from renewable resources in Alberta and it shows there are opportunities to increase the share of electricity from renewable resources.

The following electric power generation technologies were considered in the market penetration and market share assessment of Alberta's renewable energy: supercritical coal, and subcritical (both to be phased out by 2030), cogeneration, combined cycle, and simple cycle by natural gas, hydro, wind, biomass, and solar. The technical specifications of each technology were gathered from different sources and are presented in Table 5-2. The electric power generation capacity of each technology was forecasted from 2020 to 2050 based on the developed electric power demand projection models and using the most recent data from the Alberta Electric System Operator on electric power import, export, intensities, and heat loss [293].

Table 5-2: Capital and operating costs, energy demand, and GHG emissions profile of the selected electric power generation technologies in 2017

Electricity generation technology	Capital cost[a] ($/kW)	Fixed O&M[a] ($/kW)	Variable O&M[a] ($/MWh)	Maximum availability[b] (%)	Emission factor (tonnes of CO_2 eq. per MWh)	Lifetime	References
Subcritical coal	1,244	35.1	13	82	1.1	15	[295-299]
Supercritical coal	1,723	35.1	12	72	1.0	19	[295-299]
Cogeneration	1,119	6.94	2.5	73	0.86	30	[295-299]
Combined cycle	1,190	6.5	1.9	82	0.81	30	[295-299]
Simple cycle	939	14.1	13.8	84	0.90	30	[296-299]
Hydro	3,014	29	0	56	0	50	[296-300]
Wind	2,203	79	0	27	0	30	[296-299, 301, 302]
Solar	3,498	45	0	16	0	30	[296-299, 301]
Biomass (forest residue)	2,130	60	52	70	1.0	30	[296-299, 303-306]
Biomass (straw)	2,300	66	47	70	1.0	30	[296-299, 303-305, 307]

a. Applicable, capital, fixed, and variable O&M costs are converted to 2010 dollars from the reference location based on Bank of Canada exchanges rates [308] and regional indices of 1.08 and 2.16 for transfer projects from the US Gulf Coast to Canada [309]. Variable O&M costs of gas-fired cogeneration, combined cycle, and simple cycle processes do not inlcude fuel costs.

b. Except for solar and biomass straw, maximum availability was assumed.

The subcritical coal plant lifetime is assumed to coincide with the proposed retirement schedule of coal-fired electricity generation.

The market penetration and market shares of the electric power generation alternatives were analyzed using the technical, environmental, and economic characteristics of each technology. The current GHG emissions profile of the electricity generation sector was also assessed to evaluate the potential impacts of carbon price and the phase-out of coal electric power plants on the future GHG emissions performance of the sector.

5.2.5 Carbon price scenario formulation

The scenarios were formulated to analyze the effects of changes in carbon price on the market penetration and market share modules from 2020 to 2050. Four carbon pricing scenarios were formulated to capture the effects of wide range of carbon price changes, from zero to \$105.52 per tonne of CO_2 eq., on market penetration, market share, energy saving, GHG emissions, and energy intensity improvement. In a zero-carbon price scenario, it is assumed no carbon price imposition. A business-as-usual (BAU) scenario considers a carbon price of \$15 per tonne of CO_2 eq. from 2020 to 2050. In the low carbon price scenario, \$30 per tonne of CO_2 eq. was considered, while the high carbon price scenario sets a price of \$30 per tonne of CO_2 eq. in 2020 and this price increases with the annual growth rate of 4% between 2020 and 2050. This wide range of carbon prices from zero to \$105.52 per tonne of CO_2 in the zero and high carbon price scenarios was considered to analyze the impact on the market penetration of renewable technologies.

5.3. Results and discussion

In this section the results from the three modules are presented. The total electricity demand module identifies the key factors that influence the future electricity market. The statistical test results, model validation, and total electricity demand forecasts between 2020 and 2050 are explained. The results from market penetration and market share include the electric power generation technologies along with their associated GHG emissions. The impacts of four carbon pricing scenarios and financial incentives on renewable power generation and installation are described at the end.

5.3.1 Total market demand module results

As explained in the method section, total electricity demand is modeled based on the statistical analysis to select the main parameters for developing dynamic econometric functions. The modelling involves 7 parameters, 6 statistical tests, and 3 input variables that are solved using Eqs. 5-1 and 5-3.

Statistical analysis results

The results from the models were analyzed through the least squares analysis and a series of statistical tests. The following aspects were evaluated: the validity of individual variables used in mathematical equations, the validity of the developed mathematical functions as one equation, and the serial correlation among the residuals. Table 5-3 shows the results of the statistical tests with the key factors that can affect Alberta's total electricity demand. Based on the statistical tests shown in Table 5-1, electricity price, GDP, and population are three parameters most influencing electricity demand in Alberta, hence they are used to develop the dynamic econometric function as described in Eq. (5-5). The function uses the 25-year time series data (1990-2015) of Alberta's electricity demand, electricity price, and GDP to forecast the total electricity demand up to 2050.

$$ln\,(E(t)) = -5.4935 + 0.4487 \times ln\,(GDP(t)) - 0.1689 \times ln(EP(t)) + 0.3985 \times ln\,(Popu(t)) \quad \textbf{Eq. 5-5}$$

Here, *E(t)* is Alberta's electricity demand in year t, *GDP(t)* is Alberta's gross domestic production in year t, *EP(t)* is Alberta's average electricity price in year *t*, and Popu(t) is Alberta's population in year t.

Table 5-3: Potential effective factors on Alberta's electricity demand along with their statistical and probability test results

Model variables	a	b	Prob. (a)	Prob. (b)	R-squared	Adj R-Squared	Prob. (F-Stat.)	Durbin Watson Stat.
Electricity price [310]	3.467	-0.389	0.000	0.000	0.800	0.792	0.000	0.978
Electricity share in total energy use [311]	3.399	0.851	0.000	0.000	0.742	0.730	0.000	0.849
Gross domestic production [312]	-0.735	0.485	0.000	0.000	0.923	0.920	0.000	1.002
Natural gas price [310]	3.991	0.252	0.000	0.000	0.731	0.720	0.000	0.377
Natural gas share in total energy use [311]	5.794	0.649	0.000	0.064	0.140	0.103	0.064	0.148
Population [313]	-7.322	0.837	0.000	0.000	0.911	0.907	0.000	0.974
Gasoline price [310]	3.550	0.354	0.000	0.000	0.638	0.623	0.000	0.551

Statistical test results of the developed equation are presented in Table 5-4. The Adj. R-squared value is close to one; this shows that the developed models cover the changes of actual data with an appropriate level of fitting. The Prob. values are less than 0.05 and the Prob. F statistic is zero. Moreover, the Durbin-Watson statistical test value is higher than 1.5, which indicates that the probability of serial correlation is very low in the developed dynamic econometric function. These results highlight the validity of the developed model.

Model validation

The validation results of the total electricity market model for electricity use in Alberta from 1998 to 2015 and demand forecast from 2020 to 2050 are presented in Figures 5-2 and 5-3, respectively. The historical data on electricity use is from the Alberta Electric System Operator (from 1998 to

2015) [293] and the forecast data is from the Canada LEAP model (from 2020 to 2040) [314]. As shown in Figure 5-2, the changes in actual consumption are covered by the electricity use output from the developed equation and they follow the changes of real data. The percentage of absolute average error (AAE%) of electricity use values from the model is 2.76, which suggests that the developed models follow the same trend as actual data. Similarly, the results from the electricity demand forecast are consistent with the forecast data from the Canada Energy Regulator and Alberta Electric System Operator (Figure 5-3).

Table 5-4: Modeling statistical tests results for the developed dynamic econometric electricity demand function for Alberta

Coefficients' values		Statistical tests' values		Statistical tests' values	
a	5.4935	Prob. a	0.0164	R-squared	0.9405
b	0.4487	Prob. b	0.0040	Adj. R-squared	0.9324
c	-0.1689	Prob. c	0.0482	Prob. F statistic	0.0000
d	0.3985	Prob. d	0.0373	Durbin-Watson statistic	1.5771

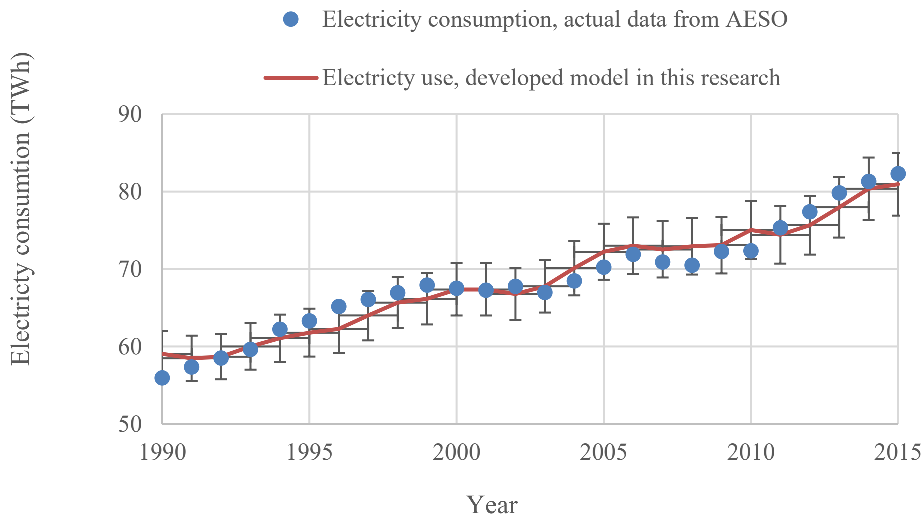

Figure 5-2: Validation of the results of the market penetration modeling of Alberta's electricity demand (1998-2015) [293]

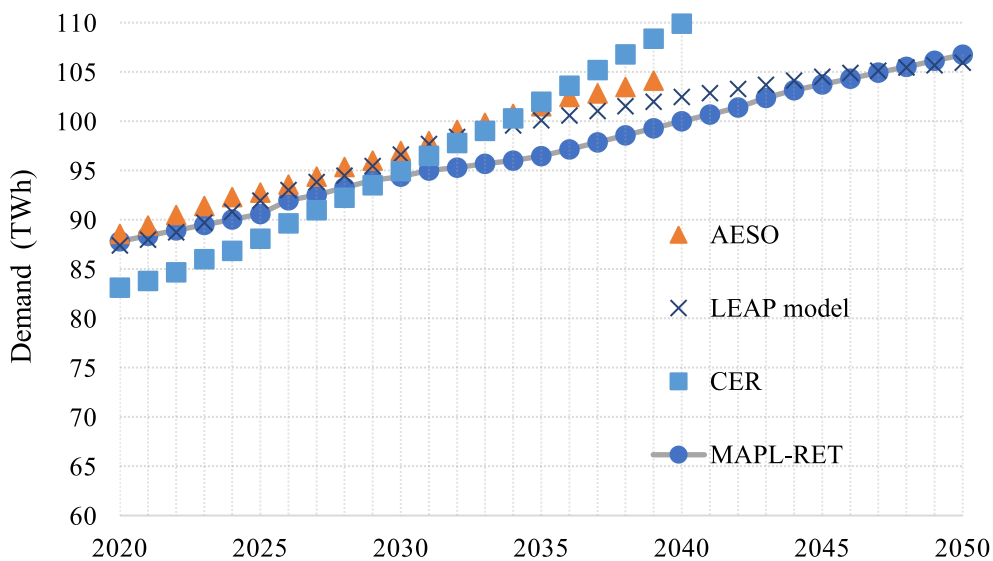

Figure 5-3: Validation of the results of the electricity demand estimate by the developed dynamic econometric function based on the data from the Alberta Electric System Operator [293], Canada Energy Regulator [294], and the Canada LEAP model [314]

The impact of macroeconomic factors on total electricity demand

In this section, the impact of key economic factors including the average electricity price, provincial GDP, and population growth on total electricity demand were analyzed using the BAU, low, and high growth rates for each factor, as summarized in Table 5-5. The growth rates were formulated based on Statistics Canada's projection reports and used historical data and forecasts [287].

Table 5-5: Growth rates for electricity price, provincial GDP, and population changes

Parameter	Low	BAU	High
Average electricity price in the demand sector [287]	Annual growth rate of 1.5%	Annual growth rate of 2%	Annual growth rate of 2.5%
Provincial GDP [288]	Annual growth rate of 1%	Annual growth rate of 1.5%	Annual growth rate of 2%
Population growth* [288]	Linear increase to 5.43 million by 2050	Linear increase to 6.18 million by 2050	Linear increase to 6.52 million by 2050

*Population growth rates are from Statistics Canada's projection report "Annual Demographic Estimates: Canada, Provinces, and Territories" [288]

Figure 5-4 shows the total electricity demand projection, calculated using Eq. (5-5), and the impacts of changes in electricity price, GDP, and population for the three scenarios (low growth, BAU, and high growth). The projected annual electric power demand growth rates are 0.62%, 0.75%, and 0.91% in the low, BAU, and high scenarios, respectively. Electricity demand in the high growth rate case is 3.98% higher than in the reference case in 2050. As shown in Figure 5-4, the impact of the high growth rate is more detectable during the later years of the time horizon because of the accumulated effects of a higher growth rate over time.

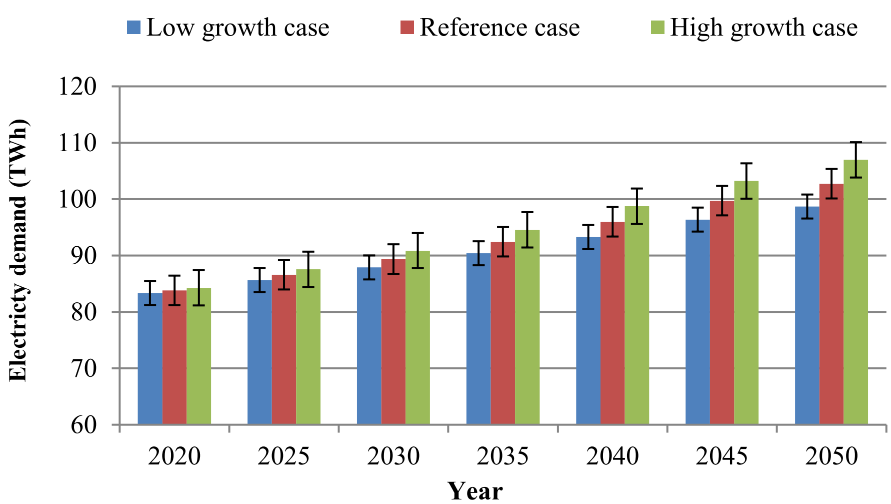

Figure 5-4: Electric power demand estimates in the low, BAU, and high growth cases

A sensitivity analysis was done to see the impact of changes in electricity price, GDP, and population values on electricity demand. The impact of changes in the main variables on penetration modeling functions is shown in Figure S5-1. The sensitivity analysis results indicate that the most important variable in the electricity demand function is GDP. Population and electricity price are other important variables. A ±20% change in GDP can make a 6.8% change in total electricity demand. Changes in population and electricity price result in changes of 6.0% and 2.4%, respectively.

5.3.2 Market penetration and market share results

The electric power generation capacities and electricity generation technology shares are analyzed in this section. Technical, environmental, and economic factors such as capital costs, operation and maintenance costs, generation capacities, merit order, carbon price, discount rate, and technology lifetime associated with electricity generation technologies were considered in the market penetration module in four carbon price scenarios using Eq. (5-4) [315]. The effects of incentives on electric power generation capacity by renewables were calculated by changing capital and operating costs. Two levels of capacity development incentive (no incentive and 1000 $ incentive per kW capacity) and electric power generation incentive (no incentive and 70 $ incentive per MW generation) from 2021 to 2025 were evaluated.

As shown in Table 5-6, both capacity development and electricity generation incentives have significant roles in increasing the share of renewable energy resources. For example, wind electric power capacity in 2030 could increased from 1507 MW in the zero carbon price scenario to 2239 MW with a 1000 $/kW incentive in capacity generation in the high carbon price scenario. Similar growths were observed in hydro, biomass, and solar electric power generation capacity development as a result of incentives in capacity development or electric power generation from renewable sources. Incentives either in capacity development or electric power generation can improve the market penetration of renewables; however, because of the huge investment requirement for renewable energy development, incentives from both electricity generation and capacity development would be more effective [316, 317].

Table 5-6: The effects of incentives put toward capacity development and electric power generation from renewable resources

Renewable energy alternatives		• No incentive for capacity development • No incentive for electricity generation				• 1000 $ incentive per kW capacity development • No incentive for electricity generation				• No incentive for capacity development • 70 $ incentive per MWh electricity generation			
		Zero carbon price	BAU carbon price	Low carbon price	High carbon price	Zero carbon price	BAU carbon price	Low carbon price	High carbon price	Zero carbon price	BAU carbon price	Low carbon price	High carbon price
Wind (MW)	2030	1507.	1511.	1515.	1518.0	2101.0	2152.9	2205.7	2239.2	1649.9	1666.1	1682.6	1693.0
	2050	1537.1	1543.4	1549.9	1559.7	2556.0	2639.5	2725.5	2854.4	1757.5	1781.9	1807.1	1842.7
Hydro (MW)	2030	906.7	907.8	909.0	909.7	1015.5	1025.4	1035.4	1041.5	942.5	946.7	951.0	953.6
	2050	913.3	915.0	916.7	919.0	1077.7	1091.9	1106.5	1125.2	967.9	974.0	980.4	988.9
Biomass (MW)	2030	427.3	429.5	431.7	433.1	688.0	711.1	734.7	749.9	495.4	503.4	511.6	516.8
	2050	445.0	448.5	452.2	458.0	913.2	952.1	992.1	1054.9	554.5	567.0	580.0	599.2
Solar (MW)	2030	1131.9	1132.1	1132.4	1132.5	1147.5	1149.0	1150.5	1151.4	1137.1	1137.8	1138.5	1138.9
	2050	1133.5	1133.9	1134.3	1134.8	1158.0	1160.3	1162.5	1165.6	1141.2	1142.2	1143.2	1144.6

The market share results for the high carbon price scenario are presented in Figure 5-5. The results are based on a 1000 $/kW incentive in capacity development and 70 $/MWh incentives in electricity generation from 2021 to 2025. The phase-out of coal electric power plants was considered for the years 2030 to 2050.

Implementing a high carbon price can significantly facilitate the market penetration of low carbon and renewable energy technologies. That said, the impact of incentives is much higher than the effects of a carbon price on the market penetration of renewable energies, as shown in Figure 5-5 and Table 5-6. For instance, implementing a 1000 $/kW capacity development incentive and a 70 $/MWh electric power generation incentive for renewable energies from 2021 to 2025 can increase the market shares of wind, one of the most competitive renewable technologies, to 4943, 5113, and 5213 MW in the BAU, low, and high carbon price scenarios, respectively. Implementing 968 $/kW and 70 $/MWh incentives on electric power capacity development and electricity generation from renewable resources, along with a high carbon price, can lead to 5000 MW electric power generation capacity from wind turbines. Moreover, a financial incentive and the high carbon pricing scenario as well as phasing out coal-based power plants can increase the share of renewable energies from 12.5% in 2018 to 30% in 2030 on the electricity supply side. Annual growth rates of renewable energies are higher than those in fossil fuel-based electric power generation technologies (Table 5-7).

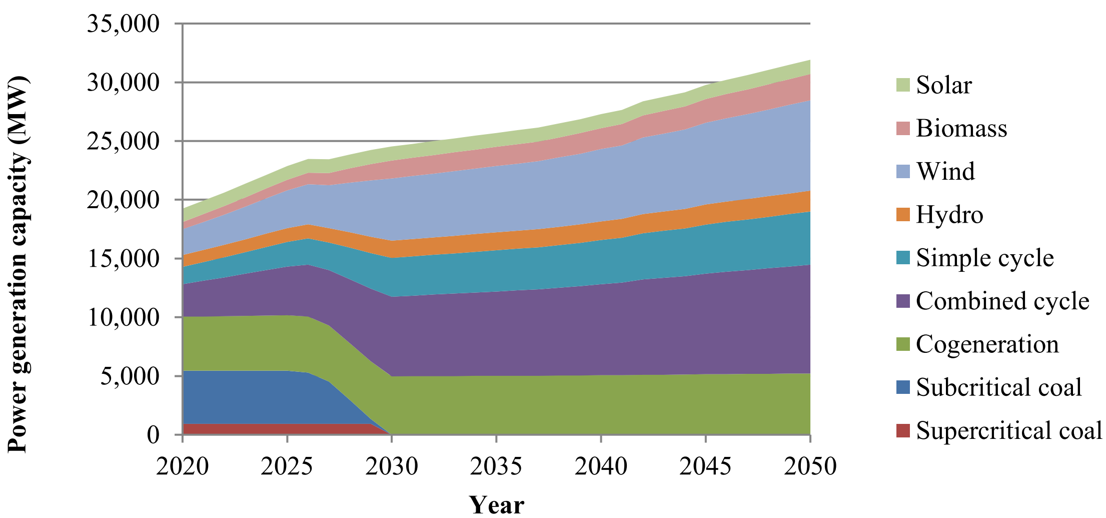

Figure 5-5: Electricity generation capacities by technology considering 1000 $/KW and 70 $/MWh incentives in renewable resource development from 2021-2025 and the phase-out of coal electric power plants by 2030 in the high carbon price scenario

Table 5-7: Annual growth rates of electric power generation by technology from 2020-2050, with 1000 $/KW and 70 $/MWh incentives in electric power capacity development and electricity generation from renewable resources

Electricity generation technologies	Average annual growth rate (%)			
	No carbon price scenario	BAU carbon price scenario	Low carbon price scenario	High carbon price scenario
Cogeneration	0.48	0.47	0.46	0.45
Combined cycle	14.16	13.66	13.17	12.58
Simple cycle	10.05	10.05	10.03	9.97
Hydro	2.39	2.54	2.68	2.85
Wind	10.17	10.77	11.37	12.15
Biomass	14.33	13.95	13.58	13.04
Solar	0.17	0.18	0.19	0.21

5.3.3 GHG emissions analysis

GHG emissions were calculated based on the emission factor of each electric power generation technology. The impacts of incentives and carbon pricing policies on total GHG emissions from the electric power generation sector were analyzed and the results are shown in Figure 5-6 and Table 5-8.

In all four scenarios, the GHG emission shares from cogeneration and combined cycle are higher than from other alternative technologies. As the carbon price per unit of CO_2 emissions increases, the share of environmentally friendly technologies increases, thereby reducing GHG emissions. As shown in Table 5-8, the average annual GHG emissions' growth rate from the market penetration of electric power generation technologies from 2020 to 2050 is less than zero because of the fast market penetration of renewable resources and phasing-out of coal-based electric power plants. An analysis of the accumulated results shows that carbon pricing policies have positive impacts not only on GHG mitigation but also on primary energy use in fossil fuel-based electric power generation, as shown in Table 5-8. The GHG emissions from the electric power generation sector with no incentives from 2020 to 2050 are 1,562.5 Mt CO_2 eq. Implementing incentives can mitigate the emissions to 1387.2 Mt of CO_2 eq. Therefore, the proposed incentives can lead to 175.3 Mt CO_2 eq. mitigation from 2020 to 2050. The effects of implementing carbon pricing policies and incentives on accumulated GHG mitigation are shown in Table 5-9.

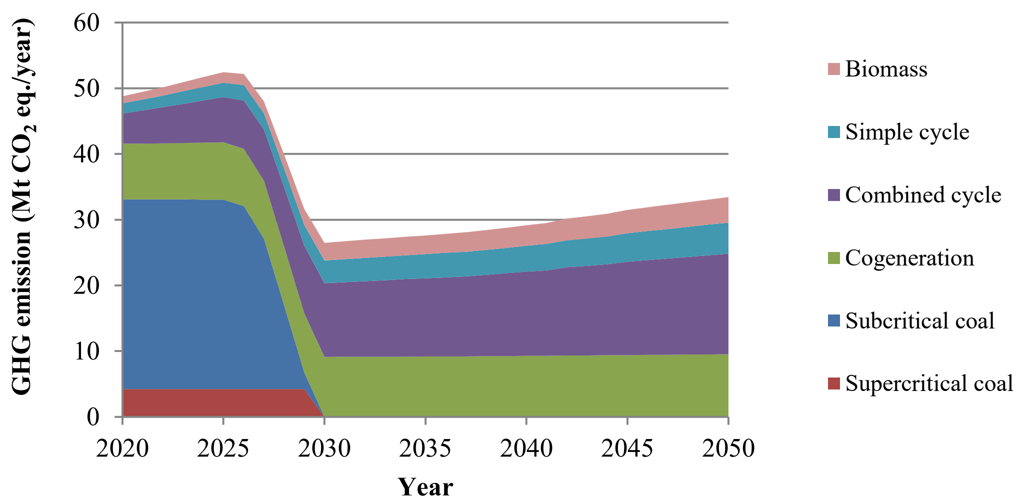

Figure 5-6: GHG emissions from electricity generation technologies assuming 1000 $/KW and 70 $/MWh incentives from 2021-2025 toward electric power capacity development and electricity generation from renewable resources for Alberta from 2020-2050 (high carbon price scenario)

Table 5-8: Annual growth rates of GHG emissions with incentives of 1000 $/KW and 70 $/MWH in electric power capacity development and electricity generation from renewable resources for Alberta from 2020-2050

Electricity generation technologies	Average annual GHG emission growth rate (%)			
	No carbon price scenario	BAU carbon price scenario	Low carbon price scenario	High carbon price scenario
Cogeneration	0.46	0.45	0.44	0.43
Combined cycle	14.05	13.55	13.07	12.47
Simple cycle	9.96	10.00	10.02	10.01
Biomass	14.21	13.84	13.47	12.93
Total	**-0.58**	**-0.62**	**-0.66**	**-0.70**

Table 5-9: The effects of carbon pricing policies and incentives on accumulated GHG mitigation

Carbon pricing policies	Zero incentive on renewable energies		$400/kW for capacity development and $30/MW for electricity generation		$1000/kW for capacity development and $70/MW for electricity generation	
	Average annual GHG emissions growth rate (%)	Abatement GHG mitigation vs. BAU carbon price (Mt)	Average annual GHG emissions growth rate (%)	Abatement GHG mitigation vs. BAU carbon price (Mt)	Average annual GHG emissions growth rate (%)	Abatement GHG mitigation vs. BAU carbon price (Mt)
No carbon price scenario	-0.08	-2.25	-0.11	-3.09	-0.58	-12.36
BAU carbon price scenario	-0.09	---	-0.12	---	-0.62	---
Low carbon price scenario	-0.10	2.16	-0.13	3.01	-0.66	11.91
High carbon price scenario	-0.10	3.86	-0.14	5.46	-0.70	21.37

The MAPL-RET framework can also be used for other energy technologies on the power supply side with adjustment needed depending on the specifications and characteristics of the energy system. For example, the electricity demand market module assesses the main parameters affecting electricity demand that are specifically related to the electric power supply side. Likewise, scenario formulation and carbon pricing can differ by jurisdiction. Therefore, it is important to adjust the model when using this framework in other jurisdictions.

The developed model is data-intensive; this is a limitation when there is insufficient data. The lack of data is more critical when analyzing the low technology readiness level of emerging technologies.

5.4. Conclusions

The world is facing the unprecedented challenge of limiting the global temperature rise well below 2 $^{\circ}$C above pre-industrial levels in order to avoid the adverse impacts of climate change. There is scientific consensus that greenhouse gas emissions due to human activity are the main drivers of these climate change impacts. With two-thirds of the emissions attributed to fossil fuels, the energy system requires a deep decarbonization. Energy efficiency improvement and a transition to low carbon energy sources are the two critical pathways. Renewable energy technologies have an immense role in the energy transition, but there are technical, environmental, and socio-economic challenges in their wide deployment. These need to be incorporated when studying the future market adoption potential of renewable energy technologies in a particular jurisdiction. This paper proposed a novel framework to systematically analyze how policy measures such as carbon price and economic incentives affect the penetration of renewable technologies and the GHG mitigation potential in an electric power sector. Alberta, a fossil-dominated province in Western Canada, was chosen for a case study to demonstrate the framework. MArket Penetration ModeLling of Renewable Energy Technologies in Electric Power Sector (MAPL-RET) is comprehensive and data intensive and comprises three modules: the total electricity demand module, market penetration module, and market share module.

Implementing a carbon price in the electric power generation sector and providing investment incentives for renewable energy and phasing out coal-fired electricity generation can increase the market shares of low carbon energy technologies and consequently can mitigate 23.6 Mt and 29.1 Mt of CO_2 eq. in 2030 and 2050, respectively in Alberta's electricity generation sector. A carbon price on fossil fuel and incentives on clean energy technologies can help to achieve 5000 MW electric power generation from wind turbines by 2030. Annual GHG mitigation rates are 0.44, -0.45, -0.47, and -0.50 Mt/year, in the zero, BAU, low, and high carbon price scenarios, respectively. The developed framework can help policy makers to achieve GHG mitigation plans by considering technical and economic parameters, carbon price, and incentives.

It is worth mentioning that the proposed framework can also be used for the electric power sector in other jurisdictions with adjustment in the models and data used; this mainly depends on the technological specification and characteristics of the energy system. The scenario formulation can also be adjusted based on the focus of the policy measure to be analyzed. The other aspect that needs to be considered is the data -intensiveness of the framework; this requires gathering macroeconomic as well as technology-specific environmental and cost data. The latter is sometimes difficult to obtain, especially for energy technologies at their early stage of development.

Chapter 6 : Conclusions and Recommendations for Future Research

6.1. Conclusion

In this research, the research on the market penetration modeling of energy technologies was reviewed and the main advantages and disadvantages of different methods were analyzed. In addition, market penetration potentials of energy technologies were modeled; several methods were combined to achieve greater accuracy, especially for long-term forecasts in four different sectors, the residential, commercial, industrial, and electric power generation sectors. These models were developed to fill a gap in the research and to determine the effective factors on the market penetration of energy technologies. The developed models can analyze the effects of incentives, subsidies, tax-free policies, and carbon price, as well as related economic and technical factors on the market penetration of energy technologies. The key highlights are described below.

6.1.1. Literature review of market penetration modeling of energy technologies

The published research on market penetration models of energy technologies was systematically reviewed and analyzed. Based on the review outcome, a new integrated model that comprises time series, econometric, and cost models to assess market penetration level was developed (see Figure 6-1).

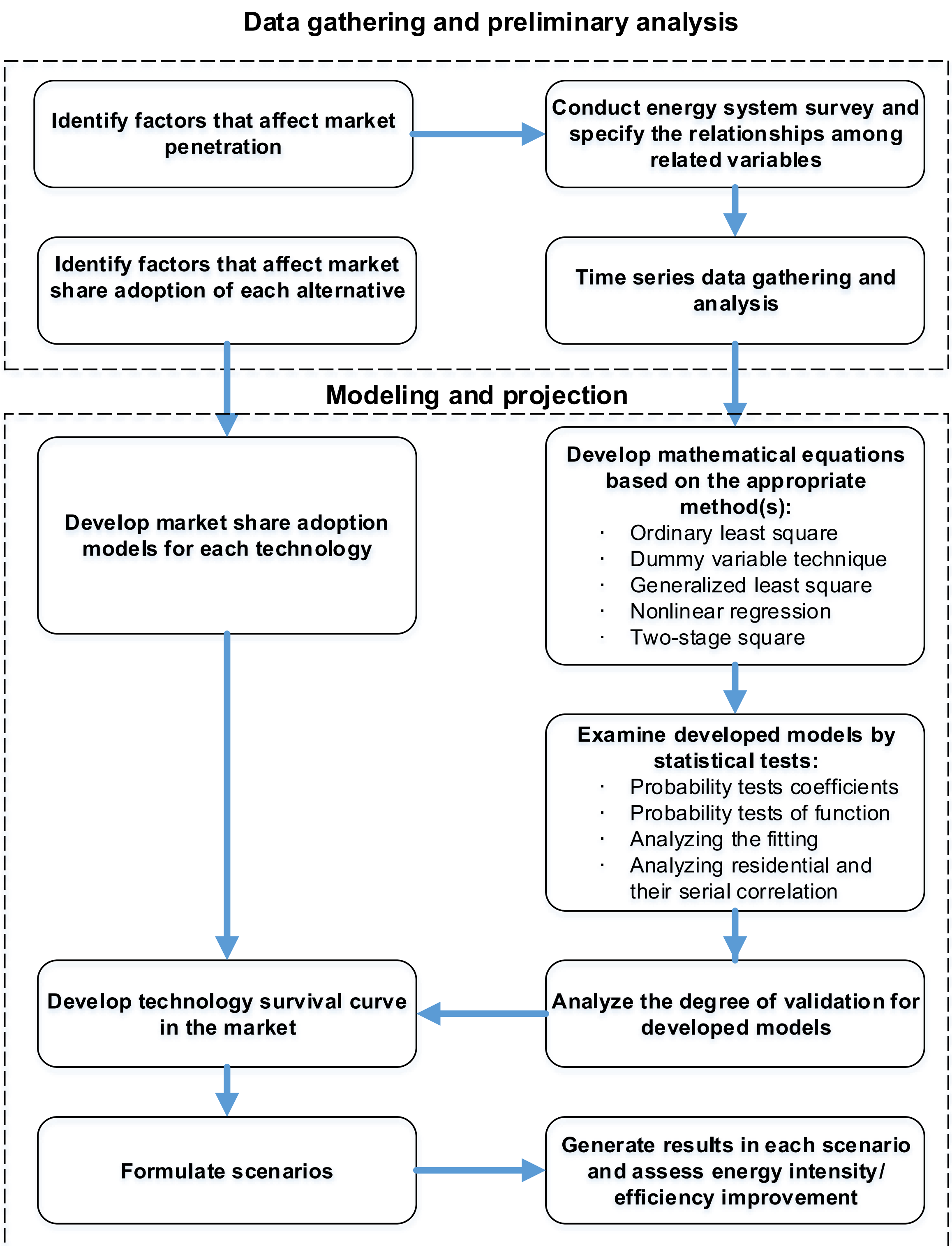

Figure 6-1: Hybrid model developed to assess the market penetration of energy technologies

A new hierarchy framework was developed to model the market penetration of energy technologies. As a case study, the framework was applied to evaluate the market penetration of electrical furnace heaters in the residential sector in Alberta, Canada with a focus on single detached houses. The developed methods and categorized tools would be useful for researchers in different jurisdictions using available data and energy system characterizations.

The review results highlight the fact that reliable energy technology market penetration modeling is not based on individual factors but is a complex procedure influenced by many different factors. There are market penetration models; however, these do not accurately assess the potential impacts of different energy policies such as incentives, subsidies, taxes, and carbon levies. The future market penetration potential of new energy technologies could be modeled by combining several different methods to achieve greater accuracy, especially for long-term forecasts.

6.1.2. Market penetration modeling of energy technologies in the residential sector

An approach to model the market penetration of high efficient residential sector appliances was developed. The impacts of changes of macroeconomic parameters, appliance price, electricity price, and incentives on average energy efficiency improvement for major residential sector appliances were studied. This research provides the results of market penetration modeling of high energy efficient appliances in Alberta's residential sector for the years 2012-2050 (see Figure 6-2).

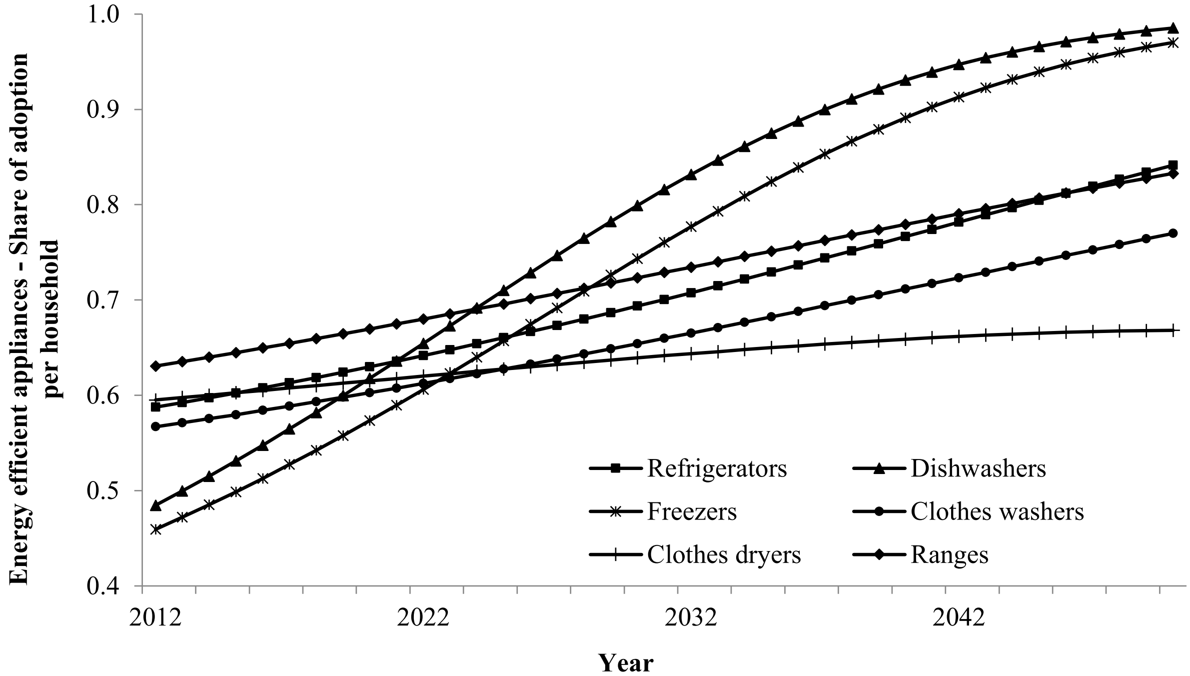

Figure 6-2: The adoption shares of high energy efficiency appliances (2012-2050)

A combined method based on energy system parameters, econometric market penetration models, and market share functions was developed. Even though 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, 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 high for almost all appliances in the first years of the study period. Clothes dryers and refrigerators have a high 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. It was observed that using prices in our research helped achieve a higher level of accuracy in modeling – up to 93% in our developed model for clothes washers.

6.1.3. Market penetration of energy technologies in the oil sands production industry

MAPL-OET, a new data-intensive market penetration and market share model, was developed to analyze the market penetration of energy technologies in the industry sector. MAPL-OET comprises three major modules: total market for oil sands, market penetration, and market share. The model was applied to commercial scale and emerging energy technologies in the oil sands industries to forecast their market penetration and market shares from 2018 to 2050. The impacts of new energy technologies' market penetration on energy saving, GHG mitigation, and energy intensity improvement were analyzed. The results show that the implementation of a high carbon price in oil sands industry can facilitate the market penetration and market share of environmentally friendly technologies and may not hugely impact overall bitumen production. The comparative assessment of the BAU and the high carbon price scenarios shows that carbon price can help Canada save 3196 PJ of energy and mitigate 192.8 MT of CO_2 eq. GHGs between 2018 and 2050. As summarized in Figure 6-3, average energy intensities will grow annually by -1.01% and -1.31% in the BAU and high carbon price scenarios, respectively. In 2050, the average energy intensity in the high carbon price scenario will be 25.8% lower than in the BAU scenario. The developed new framework can help public and private organizations achieve energy or environmental targets as it allows users to analyze the market penetration of available technologies and retrofitting alternatives.

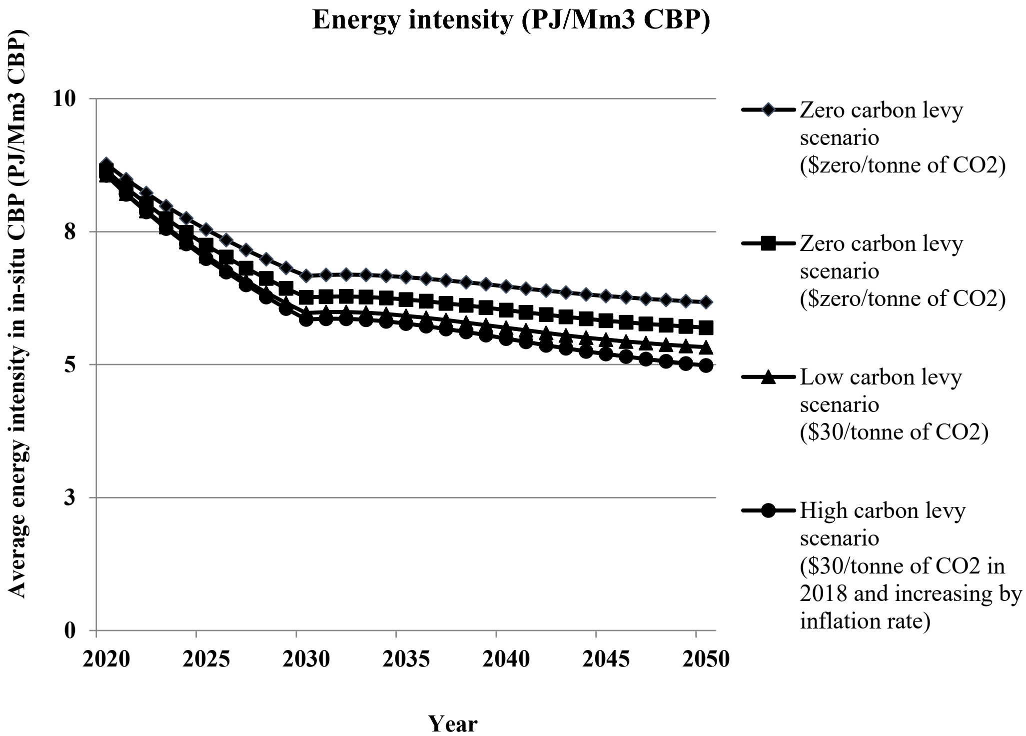

Figure 6-3: Energy intensity improvement in in situ crude bitumen production (2016-2050)

6.1.4. Market penetration of electricity generation technologies in the power sector

The comprehensive, data-intensive MAPL-RET model was developed to analyze the impact of changes in economic, technical, and environmental factors on Alberta's power generation technologies for the years 2020 to 2050. Implementing a carbon price in the power generation sector, providing investment incentives for renewable energy, and phasing out coal-fired electricity generation can increase the market shares of low carbon energy technologies and consequently reduce 23.59 Mt and 29.09 Mt of CO_2 eq. emissions by 2030 and 2050, respectively. A carbon price on fossil fuel and incentives on clean energy technologies can help in the penetration of 5000

MW of wind turbines by 2030 (see Figure 6-4). Annual GHG mitigation rates are 0.44, -0.45, -0.47, and -0.50 Mt/year, in the zero, BAU, low, and high carbon price scenarios, respectively. The developed model can be used by policy makers to develop GHG mitigation plans incorporating technical and economic parameters, carbon price, and incentives.

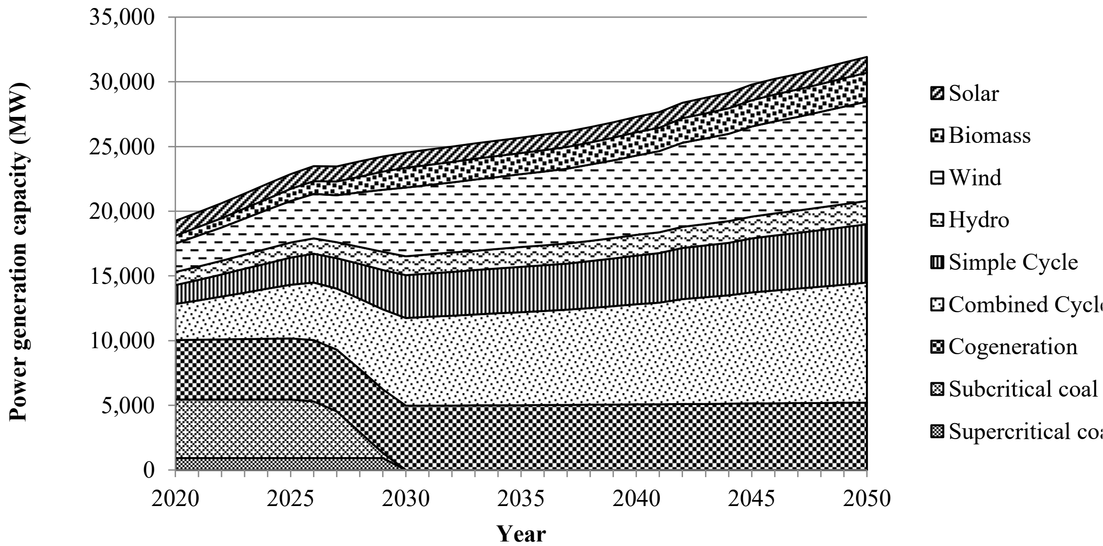

Figure 6-4: Electricity generation capacities for different technologies with 1000 $/KW and 70 $/MWh incentives for renewable resource development from 2021 to 2025 and the phase-out of coal electric power plants by 2030 from 2020 to 2050 for Alberta – high carbon price scenario

6.2. Recommendations for future work

The following are the recommendations for future research.

- Combined models can be extended to analyze the market penetration of energy technologies in the main energy sectors (e.g., residential, commercial, industry, agriculture and forestry, and transportation) and energy sub-sectors such as space heating and cooling.

Moreover, the effects of changes in economic and technical factors on the market penetration of energy technologies could be investigated locally, provincially, and nationally.

- Changes in the shares of specific technologies in the energy system can lead to fuel switching. Therefore, these models can be extended to analyze the effects of the market penetration of energy technologies on fuel switching in the main energy sectors or sub-sectors.
- The development of GHG mitigation scenarios in the energy demand and supply sectors should consider the market penetration of technologies through the development of data-intensive models.

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Appendices

Appendix 1: Supplementary information for Chapter 4

Table S4-1: List of statistical tests to analyze effective variables in market penetration modeling [211]

Prob.	It analyzes the probability of ineffectiveness of individual variables used in modeling. Values lower than 0.05 indicate that the related variable has a significant role in modeling.
R-squared (R^2) and *Adj. R-squared* (Adjusted R^2)	It analyzes the fitting degree of actual data by the developed model. The best value of these statistical tests in fitting is one. Adj. R-squared is useful to analyze the fitting degree when the amount of actual data is relatively high
The *F-statistic* test	It analyzes the developed structure of the model by assuming that all the coefficients in the developed model (excluding the constant, or intercept) are equal to zero. Values lower than 0.05 are accepted.
The Durbin-Watson (DW)	It detects the serial correlation among the residuals: $$\mathrm{DW} = \frac{\sum_{i=2}^{N}\left(\hat{\varepsilon}_i - \hat{\varepsilon}_{i-1}\right)^2}{\sum_{i=1}^{N}\hat{\varepsilon}_i^2}$$ ε is the residual value in each point. The residual value is the difference between actual data and modeled results at each point. DW values below 1.0 are evidence of positive serial correlation.

Table S4-2: Emission factors of each major technologies in oil sands extraction

Technology	NG consumption (MJ/m^3 bitumen)	Elec. consumption (MJ/m^3 bitumen)	Total energy consumption (MJ/m^3 bitumen)	GHG emission (Tonnes CO_2/m^3 bitumen)	Sources
Surface mining	2978.77	300.88	3526.09	0.18	[5]
SAGD	12551.55	362.60	7297.40	0.55	[5]
CSS	---	---	8027.14	0.61	[5]
SBE*	508.40	439.70	948.10	0.13	[48]
EHBE *	199.13	2716.43	2232.00	0.56	[49]

Table S4-3: Historical data of global population, global GDP, and crude bitumen reserves in Canada [259, 318]

Year	Global population	North America population	World GDP at market prices (constant 2005 $US)	Crude bitumen reserves		
				In situ (10^6 m^3)	Mineable (10^6 m^3)	Total (10^6 m^3)
1990	5,309,667,699	280,633,063	3.09E+13	57.4	467	524.4
1991	5,398,328,753	283,504,655	3.14E+13	50.7	451	501.7
1992	5,485,115,276	286,385,887	3.20E+13	48.2	434	482.2
1993	5,570,045,380	289,332,529	3.25E+13	40.6	417	457.6
1994	5,653,315,893	292,421,641	3.35E+13	166.2	399	565.2
1995	5,735,123,084	295,699,810	3.45E+13	195.1	379	574.1
1996	5,815,392,305	299,199,293	3.57E+13	300.7	360	660.7
1997	5,894,155,105	302,879,380	3.70E+13	274.0	340	614.0

Year	Global population	North America population	World GDP at market prices (constant 2005 $US)	Crude bitumen reserves		
				In situ (10^6 m^3)	Mineable (10^6 m^3)	Total (10^6 m^3)
1998	5,971,882,825	306,624,987	3.79E+13	449.3	886	1335.3
1999	6,049,205,203	310,277,111	3.92E+13	498.1	1393	1891.1
2000	6,126,622,121	313,724,124	4.09E+13	491.2	1370	1861.2
2001	6,204,310,739	316,914,463	4.16E+13	486.7	1346	1832.7
2002	6,282,301,767	319,886,820	4.25E+13	522.6	1316	1838.6
2003	6,360,764,684	322,729,927	4.37E+13	440.6	1280	1720.6
2004	6,439,842,408	325,577,654	4.55E+13	422.0	1239	1661.0
2005	6,519,635,850	328,524,304	4.71E+13	415.0	1203	1618.0
2006	6,600,220,247	331,600,238	4.90E+13	386.3	2953	3339.3
2007	6,681,607,320	334,766,279	5.10E+13	592.6	2907	3499.6
2008	6,763,732,879	337,964,083	5.17E+13	560.7	3738	4298.7
2009	6,846,479,521	341,105,761	5.06E+13	527.0	3689	4216.0
2010	6,929,725,043	344,129,117	5.27E+13	483.5	3639	4122.5
2011	7,013,427,052	347,016,566	5.42E+13	476.4	3587	4063.4
2012	7,097,500,453	349,793,414	5.54E+13	418.6	3690	4108.6
2013	7,181,715,139	352,491,844	5.67E+13	375.4	3634	4009.4
2014	7,265,785,946	355,161,293	5.82E+13	309.6	3435	3744.6
2015	7,349,472,099	357,838,036	5.80E+13	434.5	3367	3801.5
2016	7,445,015,236	280,633,063	5.80E+13	349.2	340.1	3850.4

Table S4-4: Oil consumption in the World, North America, Asia and Oceania, and China [259, 319]

Year	Oil consumption (1000bbl/day)	North America oil consumption (1000bbl/day)	Asia and Oceania (1000bbl/day)	China oil consumption (1000bbl/day)	US imports of crude oil (1000bbl/year)
1990	66,090	20,790	13,140	2,380	1,869,005
1991	66,537	20,318	13,797	2,296	2,132,761
1992	67,189	20,128	14,414	2,499	2,151,387
1993	67,396	20,519	15,194	2,662	2,110,532
1994	67,618	20,800	16,033	2,959	2,226,341
1995	69,007	21,404	17,054	3,161	2,477,230
1996	70,255	21,333	17,979	3,363	2,578,072
1997	71,877	21,990	18,809	3,610	2,638,810
1998	73,589	22,456	19,586	3,916	2,747,839
1999	74,272	22,858	19,337	4,106	3,002,299
2000	75,973	23,586	20,279	4,364	3,177,584
2001	76,924	23,813	20,872	4,796	3,186,663
2002	77,730	23,755	21,143	4,918	3,319,816
2003	78,451	23,828	21,591	5,161	3,404,894
2004	80,091	24,213	22,435	5,578	3,336,175
2005	83,058	25,042	23,717	6,437	3,527,696
2006	84,588	25,224	24,257	6,795	3,692,063
2007	85,592	25,113	24,849	7,263	3,695,971
2008	86,788	25,255	25,475	7,480	3,693,081
2009	86,093	23,986	25,317	7,697	3,661,404
2010	85,033	23,081	25,727	8,070	3,580,694
2011	88,216	23,598	27,489	8,938	3,289,675
2012	89,127	23,363	28,406	9,504	3,362,856
2013	90,392	23,007	29,762	10,175	3,261,422
2014	91,195	23,438	30,124	10,480	3,120,755
2015	93,836	23,891	30,812	10,794	2,821,480
2016	95,456	24,764	31,514	11,231	2,680,626

Table S4-5: Natural gas consumption and price [259, 318, 319]

Year	World natural gas consumption (Billion cubic feet)*	North America natural gas consumption (Billion cubic feet)*	Asia & Oceania natural gas consumption (Billion cubic feet)*	US Henry Hub gas price ($US/MMBtu)**	Alberta average plant gate ($CAN/MMBtu)**
1990	72,670.8	22,426.6	5,295.1	1.67	1.45
1991	73,542.3	22,469.6	5,816.1	1.54	1.18
1992	75,349.9	22,911.5	6,314.3	1.79	1.22
1993	75,305.1	23,782.5	6,574.9	2.13	1.89
1994	76,893.2	24,457.2	6,988.6	1.92	1.83
1995	76,986.4	25,010.8	7,566.1	1.62	1.18
1996	79,028.6	26,122.1	7,991.4	2.50	1.54
1997	81,007.3	26,628.9	8,708.0	2.59	1.84
1998	81,093.9	26,802.5	9,126.9	2.06	1.90
1999	81,634.5	26,327.2	9,237.0	2.28	2.60
2000	83,777.7	26,774.7	9,942.9	4.31	4.80
2001	87,236.7	27,722.5	10,484.4	3.98	5.90
2002	87,701.5	26,755.8	10,693.8	3.36	3.89
2003	91,337.0	27,693.4	11,626.5	5.49	6.37
2004	93,756.0	27,289.6	12,198.5	5.90	6.62
2005	96,904.5	27,397.3	12,810.6	8.60	8.43
2006	99,486.5	26,814.4	13,741.0	6.75	6.87
2007	102,038.5	26,840.4	15,188.3	6.95	6.41
2008	105,545.4	28,179.4	16,871.0	8.85	7.90
2009	108,917.0	28,343.4	17,572.6	3.95	3.95
2010	105,326.0	28,044.5	18,518.9	4.40	3.90
2011	113,857.7	29,187.9	20,676.9	4.00	3.50
2012	116,395.2	29,883.6	22,220.4	2.75	2.25
2013	119,696.3	31,500.9	22,788.9	3.75	3.00
2014	121,357.1	32,103.4	23,626.8	4.40	4.20
2015	123,156.8	33,426.6	24,295.1	3.30	3.30
2016	124,152.3	34,469.6	25,816.1	3.80	3.80

Table S4-6: Renewable energy production in the world, in Asia, and in North America [319]

Year	Total renewable energy production (Billion kWh)	Asia renewable energy production (Billion kWh)	North America renewable energy production (Billion kWh)
1990	135.0	23.0	77.0
1991	145.0	24.0	84.0
1992	158.0	24.0	90.0
1993	163.0	24.0	93.0
1994	171.0	27.0	94.0
1995	179.0	33.0	92.0
1996	185.0	35.0	93.0
1997	200.0	38.0	95.0
1998	212.0	40.0	96.0
1999	227.0	45.0	99.0
2000	249.0	49.0	102.0
2001	264.0	52.0	100.0
2002	295.0	55.0	110.0
2003	319.0	59.0	112.0
2004	354.0	63.0	116.0
2005	391.0	74.0	121.0
2006	436.0	81.0	130.0
2007	495.0	90.0	139.0
2008	556.0	120.0	159.0
2009	643.0	148.0	181.0
2010	774.0	194.0	209.0
2011	944.0	257.0	248.0
2012	1,078.0	300.0	261.0
2013	1,273.0	390.0	303.0
2014	1,378.0	452.0	352.0
2015	1,410,0	522.0	394.0
2016	1,495.0	590.0	465.0

Table S4-7: Crude bitumen production in Canada [259, 318]

Year	Mined synthetic crude (Thousand cubic metres)	Total mining bitumen (Thousand cubic metres)	Experimental & crude bitumen (Thousand cubic metres)	Total in situ mining bitumen (Thousand cubic metres)	Total Canada (Thousand cubic metres)
1990	12,091.0	12,091.0	7,856.0	7,856.0	19,947.0
1991	13,121.0	13,121.0	7,113.0	7,113.0	20,234.0
1992	13,778.0	13,778.0	7,362.0	7,362.0	21,140.0
1993	14,123.0	14,123.0	7,685.0	7,685.0	21,808.0
1994	15,190.0	15,190.0	7,810.0	7,810.0	23,000.0
1995	16,197.0	16,197.0	8,621.0	8,621.0	24,818.0
1996	16,317.0	16,317.0	9,505.0	9,505.0	25,822.0
1997	16,798.0	16,798.0	13,806.0	13,806.0	30,604.0
1998	17,871.0	17,871.0	16,364.0	16,364.0	34,235.0
1999	18,767.0	18,767.0	14,171.0	14,171.0	32,938.0
2000	18,608.0	18,608.0	16,781.0	16,781.0	35,389.0
2001	20,239.0	20,239.0	17,954.0	17,954.0	38,193.0
2002	25,599.0	25,599.0	17,560.0	17,560.0	43,159.0
2003	26,366.3	26,366.3	20,261.3	20,261.3	46,627.6
2004	37,471.7	37,471.7	21,705.7	21,705.7	59,177.4
2005	31,688.7	31,688.7	24,341.0	24,341.0	56,029.7
2006	38,051.6	38,051.6	26,697.1	26,697.1	64,748.7
2007	39,852.9	39,852.9	28,962.9	28,962.9	68,815.8
2008	38,001.2	38,001.2	31,767.1	31,767.1	69,768.3
2009	44,132.0	44,132.0	34,127.5	34,682.1	78,814.1
2010	44,826.8	44,826.8	39,099.1	40,787.2	85,614.0
2011	48,293.5	48,293.5	43,797.6	45,624.0	93,917.4
2012	50,721.5	50,721.5	51,047.1	52,857.0	103,578.5
2013	52,277.4	53,726.4	56,742.3	58,873.0	112,599.4
2014	53,142.0	57,761.0	65,312.8	67,767.5	125,528.5
2015	54,542.0	59,523.6	67,328.8	71,456.0	130,456.5
2016	55,698.0	61,734.0	71,457.0	72,987.5	132,987.8

Table S4-8: The price of different crude oil [259, 319]

Year	WTI crude oil price ($US/bbl)	US crude oil import price ($US/bbl)	Alberta heavy crude oil price ($CAN/bbl)	Average oil wellhead price ($CAN/cubic metre)
1990	19.6	34.7	---	---
1991	24.5	39.5	16.0	---
1992	21.4	32.7	9.1	120.8
1993	20.6	30.8	13.0	123.0
1994	18.6	26.5	13.3	113.2
1995	17.2	24.9	15.0	119.7
1996	18.5	26.7	17.3	132.4
1997	22.1	31.2	20.1	160.8
1998	20.6	27.4	14.4	143.9
1999	14.4	17.6	9.4	100.1
2000	19.3	24.6	19.7	150.2
2001	30.3	38.3	27.8	233.8
2002	26.0	29.5	18.1	186.2
2003	26.1	31.3	27.6	209.2
2004	31.1	35.8	27.4	223.3
2005	41.4	45.2	30.4	260.4
2006	56.6	59.5	34.4	324.6
2007	66.2	69.6	43.1	352.9
2008	72.3	77.0	44.6	375.9
2009	99.6	102.2	75.6	557.1
2010	61.8	65.4	55.3	373.8
2011	79.5	82.7	61.5	439.6
2012	95.1	108.4	67.9	524.7
2013	94.2	104.7	63.7	490.1
2014	98.0	100.1	65.3	513.8
2015	93.0	90.0	71.2	552.8
2016	48.9	46.5	39.8	302.4

Table S4-9: Forecasted oil price [259, 318, 319]

Year	WTI crude oil ($US/bbl)	Brent crude oil ($US/bbl)	Alberta Bow River Hardisty crude oil ($CAN/bbl)	Western Canadian Select crude oil ($CAN/bbl)	Alberta heavy crude oil ($CAN/bbl)	Inflation (%)	US/CAN exchange rate ($US/$CAN)
2018	62.40	65.00	60.40	59.70	52.10	2.0	0.800
2019	69.00	71.70	67.10	66.30	57.80	2.0	0.800
2020	73.10	75.80	69.10	68.20	59.50	2.0	0.825
2021	77.30	80.10	73.20	72.30	63.10	2.0	0.825
2022	81.60	84.40	77.40	76.50	66.70	2.0	0.825
2023	86.20	89.10	81.90	80.90	70.60	2.0	0.825
2024	87.90	90.80	83.60	82.60	72.00	2.0	0.825
2025	89.60	92.60	85.20	84.10	73.40	2.0	0.825
2026	91.40	94.40	86.90	85.90	74.90	2.0	0.825
2027	93.30	96.40	88.70	87.70	76.40	2.0	0.825
2028	95.10	98.30	90.40	89.30	77.90	2.0	0.825
2029	97.00	100.20	92.20	91.10	79.40	2.0	0.825
2030	99.00	102.30	94.10	93.00	81.10	2.0	0.825

Appendix 2: Supplementary section for Chapter 5

Table S5-1: Capital and operating costs, energy demand, and GHG emissions profile of the selected electric power generation technologies in 2017

Electricity generation technology	Capital cost[a] ($/kW)	Fixed O&M[a] ($/kW)	Variable O&M[a] ($/MWh)	Maximum availability[b] (%)	Emission factor (tonnes of CO_2 eq. per MWh)	Lifetime	References
Subcritical coal	1,244	35.1	13	82	1.1	15	[298, 320-322]
Supercritical coal	1,723	35.1	12	72	1.0	19	[298, 320-322]
Cogeneration	1,119	6.94	2.5	73	0.86	30	[298, 320-322]
Combined cycle	1,190	6.5	1.9	82	0.81	30	[298, 320-322]
Simple cycle	939	14.1	13.8	84	0.90	30	[298, 301, 321, 322]
Hydro	3,014	29	0	56	0	50	[298, 301, 321, 322]
Wind	2,203	79	0	27	0	30	[298, 301, 321, 322]
Solar	3,498	45	0	16	0	30	[298, 301, 321, 322]
Biomass (forest residue)	2,130	60	52	70	1.0	30	[298, 303, 304, 321-323]
Biomass (straw)	2,300	66	47	70	1.0	30	[298, 303, 304, 321-323]

c. Applicable, capital, fixed, and variable O&M costs are converted to 2010 dollars from the reference location based on Bank of Canada exchanges rates [308] and regional indices of 1.08 and 2.16 for transfer projects from the US Gulf Coast to Canada [309]. Variable O&M costs of gas-fired cogeneration, combined cycle, and simple cycle processes do not inlcude fuel costs.

d. Except for solar and biomass straw, maximum availability was assumed.

e. The subcritical coal plant lifetime is assumed to coincide with the proposed retirement schedule of coal-fired electricity generation.

Table S5-2: List of statistical tests performed [211]

Statistical tests	Description
Prob.	- Used to analyze the effectiveness of individual variables.
R-squared (R^2)	- Measures the fitting degree of the data by the developed model.
Adj. R-squared (Adjusted R^2)	- Helps analyze the fitting degree
The prob. (F-stat.) test	- Used to analyze the validity of the model structure
The Durbin-Watson (DW) statistic test $$\mathrm{DW} = \frac{\sum_{i=2}^{N}\left(\hat{\varepsilon}_i - \hat{\varepsilon}_{i-1}\right)^2}{\sum_{i=1}^{N}\hat{\varepsilon}_i^2}$$	- Used to detect the serial correlation among the residuals [212] - ε is the residual value, a difference between actual data and modeled results at each point.

Table S5-3: Alberta electric energy generation (GWH) by resource

	Resource Type							
Year	Coal	Natural Gas	Hydro	Wind	Biogas & Biomass	Sub-total Renewables	Others	Total
1985	27,798.4	3,806.3	1,385.4	0.1	396.8	1,782.3	0.4	33,387.4
1986	29,094.5	3,524.4	1,791.4	0.2	408.9	2,200.5	0.5	34,819.9
1987	30,886.2	4,164.9	1,443.6	0.3	373.7	1,817.6	0.4	36,869.1
1988	33,103.5	5,300.7	1,422.7	0.2	381.8	1,804.7	0.4	40,209.3
1989	34,002.6	7,341.1	1,589.5	0.2	377.5	1,967.2	0.6	43,311.5
1990	34,963.6	5,551.5	2,050.9	0.6	629.0	2,680.5	0.6	43,196.2
1991	36,689.5	5,129.6	2,031.8	0.7	705.2	2,737.7	0.5	44,557.3
1992	38,546.7	6,814.2	1,575.0	0.5	913.9	2,489.4	0.4	47,850.7
1993	39,187.2	6,762.4	1,792.3	1.8	920.3	2,714.4	0.5	48,664.5
1994	42,269.8	7,468.9	1,763.2	35.6	1,370.9	3,169.7	1.5	52,909.9
1995	42,460.8	6,236.8	1,999.8	54.3	1,452.6	3,506.7	1.3	52,205.6
1996	41,220.3	7,135.0	1,966.7	59.1	1,583.1	3,608.9	0.4	51,964.6
1997	43,054.2	7,654.1	1,824.3	62.0	1,628.8	3,515.1	0.4	54,223.8
1998	41,267.7	10,607.9	2,043.3	49.4	1,659.9	3,752.6	0.4	55,628.6
1999	40,276.7	10,645.3	2,181.0	64.6	1,718.0	3,963.6	0.3	54,885.9
2000	40,462.2	13,937.3	1,748.2	71.8	1,625.7	3,445.7	0.4	57,845.6
2001	41,713.3	15,493.6	1,446.3	151.0	1,619.4	3,216.7	207.0	60,630.6
2002	42,541.7	14,623.3	1,668.0	296.1	1,686.4	3,650.5	266.7	61,082.3
2003	42,345.7	17,272.7	1,733.0	374.2	1,676.5	3,783.7	248.1	63,650.3
2004	42,538.6	18,936.3	1,977.2	669.6	1,692.5	4,339.3	254.3	66,068.6
2005	43,986.2	17,161.6	2,371.8	813.1	1,725.2	4,910.1	255.9	66,313.8
2006	44,531.4	19,449.2	1,966.4	921.4	1,855.2	4,742.9	246.9	68,970.4
2007	44,278.4	19,804.6	2,113.0	1,430.3	1,870.4	5,413.7	237.9	69,734.6
2008	42,418.7	21,036.0	2,149.9	1,472.9	1,917.4	5,540.2	111.5	69,106.4
2009	41,230.7	22,689.8	1,695.3	1,557.9	1,861.5	5,114.7	227.0	69,262.2
2010	41,120.2	24,058.4	1,620.0	1,628.6	1,908.8	5,157.4	250.3	70,586.3
2011	38,859.4	25,106.8	2,035.6	2,419.1	1,972.2	6,426.9	321.3	70,714.4
2012	38,272.0	27,238.5	2,318.7	2,640.5	2,089.1	7,048.3	359.5	72,918.3
2013	39,186.4	29,028.3	2,027.8	3,107.4	2,250.1	7,385.3	404.7	76,004.7
2014	44,442.0	28,136.2	1,861.1	3,471.3	2,065.2	7,397.6	372.6	80,348.4
2015	41,378.1	32,215.4	1,745.0	3,815.6	2,148.5	7,709.2	318.1	81,620.8

Note: All data from 2010 and earlier was collected and compiled by the Alberta Energy Regulator and its predecessors.

Table S5-4: Alberta's renewable energy resource potential

Renewable Resource	Potential	References
Wind	64,000 MW	[324]
	150,000 MW	[302]
	150,000 MW	[325]
Hydro	11,600 MW	[324]
	11,800 MW	[300]
	42,030 GWh/Year	[326]
	53,050 GWh/Year	[326]
	103,360 GWh/Year	[326]
Biomass	15,500 MW	[324]
	522.9 PJ/year	[327]
	585 PJ/year	[328]
	1,204 MW	[303]
	458 PJ/year	[306]
	700 PJ/year	[307]
	21,166 GWh/Year	[329]
Geothermal	10,000 MW	[324]
	120,000 MW	
Solar	25 PJ/year	[307]

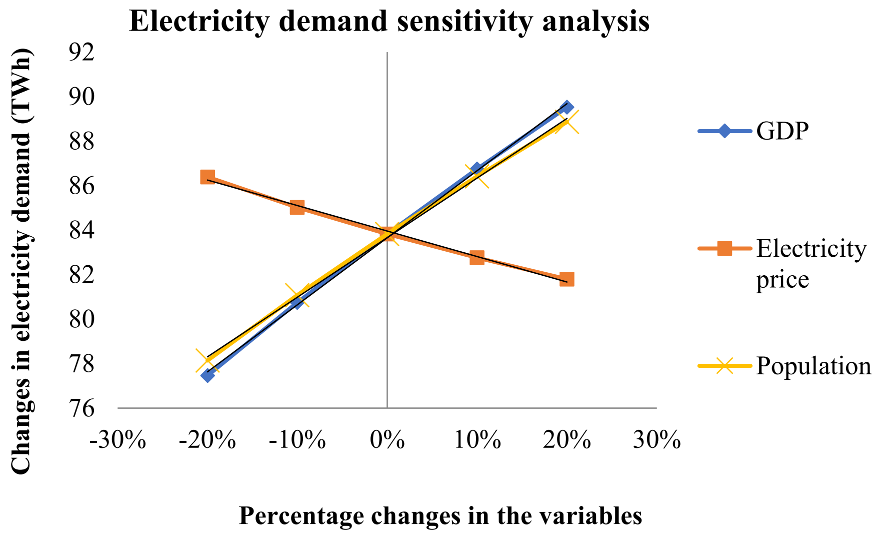

Figure S5-1: Electricity demand sensitivity analysis based on the developed dynamic econometric function