Assessment of energy efficiency improvement opportunities and the long-term potential for greenhouse gas mitigation in industrial sector

by

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Abstract

Concerns about climate change have resulted in a global agreement on the need for collective actions to reduce anthropogenic greenhouse gas (GHG) emissions. In Canada, the 9th largest global GHG emitter, the industrial sector is a major source of GHG emissions, accounting for 37% of the national emissions. This highlights the significant role the sector could play in helping Canada achieve its ambitious GHG emission reductions goals set under several international agreements.

In this study, a decomposition model was developed to analyze historical trends and the factors driving increasing emissions trends in Canada's industrial sector. While the main driver was found to be the sector's increasing activity level, fuel switching and energy efficiency improvement have contributed for emissions reduction. Historical energy efficiency improvement trends differ by sub-sector. In the past few years, the energy intensity of petroleum refining was almost constant; the iron and steel sector has benefited from structural changes, mainly due to increasing share of secondary steel production compared to primary steel production; and the cement industry has undergone changes that improved its energy efficiency by 10% in less than one decade. The analysis suggests, moreover, that Canadian chemical industries are among the best performing worldwide, mainly due to the consumption of natural gas as both feedstock and a source of energy.

A comprehensive and data-intensive framework was developed in the Long-range Energy Alternative Planning (LEAP) model to assess future GHG mitigation potential from the different industrial sub-sectors. Detailed process-level analysis was conducted for different manufacturing

industries to identify the major energy-consuming processes. The results were then used to develop energy consumption demand trees.

Long-term scenario analysis was conducted at the provincial level for the chemical and petroleum industries and national level for the cement and iron and steel industries. Baseline scenarios were developed to project long-term energy consumption and GHG emissions. The baseline scenarios were developed based on the analysis of the historical trends and by considering the confirmed governmental and sectoral development plans.

A comprehensive review was then conducted to identify the applicable energy efficiency measures in the major energy-consuming processes. For each energy efficiency measure, detailed desktop studies, industry consultation, and in some cases process simulation were carried out to assess the techno-economic performance of the measure, including energy intensity, capital, and operation and maintenance costs, and their long-term penetration in the Canadian industrial sector. These data were incorporated in the LEAP model to develop GHG mitigation scenarios and GHG abatement cost curves.

For two time periods (2010-2030 and 2010-2050), 20, 52, 28 and 22 GHG mitigation scenarios were developed for the cement, iron and steel, chemical, and petroleum refining industries, respectively. In the cement industry, the cumulative GHG emissions reduction potential was calculated to be 27.3 $MtCO_2eq$ and 59.9 $MTCO_2eq$ by 2030 and 2050, respectively. In both time periods, 70% of GHG emissions options in the sector are economically attractive. In the iron and steel sector, the implementation of energy efficiency measures was found to result in 5% GHG emissions reduction in both 2030 and 2050 time horizons. More than 90% of the overall achievable GHG emissions reductions were economically attractive. In the chemical industry, the overall cumulative GHG emissions reduction potentials were calculated to be 7.1 and 29.7 $MTCO_2eq$ by 2030 and 2050, respectively, more than three-quarters of these are economically attractive. Compared to the baseline scenario, 5% of the emissions from petroleum refining industries can be reduced by implementing different energy efficiency measures in both time periods of the study. Almost 60% of the achievable GHG emissions reduction is economically attractive.

The results of the analysis provide invaluable inputs to policy makers on the long-term potential for sectoral GHG mitigation, its associated cost, and specific areas of energy efficiency improvement to be considered when developing regional and national climate policies. In addition, with the existing and emerging environmental regulations in the carbon-constrained world, the results of this study can be effectively used by industrial stakeholders for their future investment and development decisions.

Preface

This thesis is an original intellectual product of the author, Alireza Talaei. Some parts of this work are published as follows:

A version of Chapter 2 has been submitted to the Journal of Cleaner Production as "Analysis of historical trends in Canada's industrial greenhouse gas emissions: An index decomposition analysis," coauthored by Alireza Talaei, Dr. Eskinder Gemechu, and Dr. Amit Kumar. Alireza Talaei was responsible for defining the problem, developing the model, data interpretation, and manuscript preparation with Dr. Gemechu providing intellectual guidance and support with the manuscript composition. Dr. Kumar providing supervisory oversight, intellectual guidance and support with the manuscript composition.

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A version of Chapter 5 has been submitted to Energy as "Assessment of the impacts of process-level energy efficiency improvement on greenhouse gas mitigation potential in the petroleum refining sector", coauthored by Alireza Talaei, Abayomi Olufemi. Oni, Mohammed Ahiduzzaman, Pritam Sankar Roychaudhuri, Jeff Rutherford, and Dr. Amit Kumar. Alireza Talaei was responsible for defining the problem, developing the model, data interpretation, and manuscript preparation. Dr. Oni helped develop the process simulation model and Mr. Roychaudhuri and Mr. Rutherford helped with data gathering and model verification. Dr. Kumar providing supervisory oversight, intellectual guidance and support with the manuscript composition.

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Dr. Amit Kumar was the supervisory author on this work and was involved throughout the research in concept formation and manuscript edits.

This thesis is lovingly dedicated to my wife,

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Her support, encouragement, and constant love have sustained me throughout PhD and my life.

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I take pride in acknowledging my gratitude to my colleagues at the University of Alberta Campus Food Bank, United Way, Career Center, Office of Sustainability, and Energy Club, where I had the privilege to volunteer and serve the community where I lived.

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List of Abbreviations

ACCA	Accelerated capital cost allowance
ADOE	Alberta Department of Energy
AED	Alberta Economic Development and Trade
AESO	Alberta Electric System Operator
AI-EES	Alberta Innovates - Energy and Environmental
AP	Air preheating
APEC	Asia-Pacific Economic Cooperation
App	Applicability
ASD	Adjustable speed drive
AU	Alkylation unit
BAU	Business-as-usual
BBL	Barrel
BF	Blast furnace
BOF	Basic oxygen furnace
CAD	Canadian dollar
CD	Calendar day
CDU	Crude distillation unit
CF	Cash flow
CIEEDAC	Canadian Industrial Energy End-Use Data And Analysis Center
CKD	Cement kiln dust
CO_2eq.	Carbon dioxide equivalent
COG	Coke oven gas
CRU	Catalytic reforming unit
CSC	Cost of saved carbon
CSE	Cost of saved energy
CSPA	Canadian Steel Producers Association
CWB	Complexity weighted barrel
DCU	Delayed coking unit
DRI	Direct reduced iron
EAF	Electric arc furnace
EBT	Electric bottom tapping
EC	Energy consumption
EE	Energy efficiency
EJ	Exajoule
EPA	Environmental Protection Agency
FCC	Fluid catalytic cracking
FPSC	Formulated products and specialty chemicals

GHG	Greenhouse gas
GJ	Gigajoule
HCU	Hydrocracking unit
HFO	Heavy fuel oil
HI	Heat integration
HPAD	Heat pump-assisted distillation
HTU	Hydrotreating unit
IETD	Industrial Efficiency Technology Database
IIP	Institute for Industrial Productivity
IPCC	Intergovernmental Panel on Climate Change
IU	Isomerization unit
kg	Kilogram
ktonne	kilotonne
KWh	Kilowatt hour
LEAP	Long-range Energy Alternatives Planning System
LHV	Lower heating value
LMDI	Logarithmic mean Divisia index
LTS	Low temperature shift
MDEA	Methyldethanolamine
MEA	Monoethanolamine
MMBTU	Million British thermal units
Mtoe	Million tonne oil equivalent
Mtonne	Million tonne
NAICS	North American Industry Classification System
NEB	National Energy Board
N- fertilizers	Nitrogen fertilizers
NPV	Net present value
NRC	Natural Resources Canada
NRCan	Natural Resources Canada
O&M	Operation and maintenance
PJ	Petajoule
PO	Process optimization
R&D	Research and development
Ref	Reference
SAGD	Steam-assisted gravity drainage
SEC	Specific energy consumption
SEI	Stockholm Environment Institute
SOA	State of the art
TBP	Technical best practices
TED	Technological and Environmental Database
TJ	Tera Joule

UHP	Ultra-high power
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USD	United States dollar
VDU	Vacuum distillation unit
VSD	Variable speed drive
WHR	Waste heat recovery
WSA	World Steel Association

Chapter 1 : Introduction

1.1. Background

Concerns about climate change have resulted in a global agreement on the need for collective action for reducing anthropogenic greenhouse gas (GHG) emissions. In 1988 the Intergovernmental Panel on Climate Change (IPCC) was established aiming predominantly at producing scientific information to be used by the governments to develop climate policies [1]. The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992 with the mandate of stabilizing the GHG emissions in the atmosphere at a level that prevents irreversible impacts of climate change [2]. The Kyoto Protocol in 1997 [3] and the Paris Agreement in 2015 [4] are the two international climate change commitments under the UNFCCC, both of which were ratified by a majority of United Nations member countries.

The Paris Agreement sets out to limit the global temperature rise to well below 2°C above pre-industrial levels in order to minimize the threat of climate change by the end of the current century [4]. In order to achieve this target, ambitious and aggressive global efforts are required: 50% reduction of GHG emissions by 2050, net zero emissions during the time period between 2055 and 2080, and net-negative emissions thereafter [5-8]. GHG mitigation options such as the widespread adoption of net zero/negative emission technologies like carbon capture, utilization, and storage (CCUS) and energy demand side management in buildings, transportation, and the industrial sector are identified as crucial measures to meet these targets [9].

The global industrial sector is responsible for around 40% of final energy use totals [10] and 21-24% of overall GHG emissions [10, 11] and is therefore a major contributor of global GHG emissions [12]. Different types of fuels are used in the industrial sector as direct (i.e., heat) and indirect (i.e., electricity) sources of energy as well as raw material (e.g., in the chemical and petroleum refining industries) [13]. The annual growth rate of direct energy consumption in the industrial sector was reported to be 1.3% between 2010 and 2016. Fossil fuels and electricity are the main energy sources and accounted for 71% and 20% of the global industrial energy mix in 2016, respectively. That same year, the cumulative share of solar thermal and geothermal was marginal [10].

The energy intensity (energy consumption per unit of final product) of the sector has improved in recent decades. However, due to increasing activity levels and the high fossil fuel share in the sector's fuel mix, direct GHG emissions have increased steadily over the past several years and reached 8.3 $GtCO_2eq$ in 2016. Energy consumption and associated GHG emissions trends are projected to increase in the coming decades. Compared to the 2009 level, industrial energy demand will increase by 100% and GHG emissions by 45-65% by 2050 [14]. The increasing industrial sector GHG emissions are forecast to be much higher than the annual reduction rate of 0.8% required to meet the sustainable development scenario target outlined by the International Energy Agency (IEA) [10].

This situation highlights the need for aggressive GHG emissions reduction strategies [15] and the successful implementation of climate mitigation policies [11]. Several efforts have been made at both national and regional levels to improve industrial energy efficiency and minimize the industrial sector's environmental impacts. For example, in 2017 more than 35% of global industrial energy consumption was covered by mandatory energy efficiency initiatives in which China, India, and Japan were the pioneering countries [16]. The initiatives cover different industrial sub-sectors such as cement [17], iron and steel [18], chemical, and pulp and paper and aims at reducing the sectoral emissions reductions by promoting various GHG mitigation measures.

1.1.1. Industrial energy efficiency improvement and GHG mitigation potential

There are several conventional and emerging GHG mitigation options for industrial sub-sectors [13]: energy efficiency improvement, process modification, the use of renewables, and the adoption of CCUS technologies, to name a few. Among all the options, energy efficiency improvement offers high potential for long-term emissions and cost reduction in manufacturing and non-manufacturing industries [19]. Such characteristics have attracted the attention of climate policy makers and academics.

There is considerable research on process-level energy use and GHG emissions from industrial sub-sectors (i.e., petroleum refining [20-22], iron and steel [23-25], and cement [26, 27]). Other studies use a high-level perspective and assess the potential for low-carbon technology adoption at the system level [28]. A third group of studies mainly assesses the economic performance of the energy efficiency measures using indexes such as net present value, internal rate of return, etc. [29-31].

Despite these studies, there are important gaps with respect to comprehensiveness, consistency, and applicability of existing data in the open literature for effective climate policy making. These studies do not look at the impacts of process-level energy efficiency improvement on GHG mitigation potential at the system level. Moreover, the high-level economic performance of an energy efficiency measure cannot be assessed unless its adoption potential and economic performance are analyzed in a system setting. These, along with the impacts of the interaction between energy supply and demand sectors on industrial GHG emissions, are not usually part of industrial energy efficiency studies. These research gaps could be addressed by conducting sector-specific energy and environmental analysis and developing long-term climate policy measures.

1.1.2. Energy modelling in industrial sector

Developing long-term climate policies is a complex process and requires the consideration of a comprehensive and interactive set of factors. Fact-based scenario analysis could help to address this challenge by highlighting a spectrum of possibilities and the effectiveness of the identified GHG emission reduction options. Energy modelling is a proven technique for scenario analysis, energy forecasting, and assessing the future development of an energy system [32-35]. The technique has been widely used in global, national, and regional energy planning [36-39].

Energy modelling studies broadly focus on energy supply [40-48], demand [49-58], or both [59, 60]. For example, while some studies focus solely on the long-term development of the energy supply sector [40-48], the focus of the other group of studies is on system analysis of the energy system [61] and energy forecasting in the demand side (i.e., residential [62], commercial [63], transportation [64] sector, etc.) [49-58]. A number of researches analyze the development of overall energy system [59, 60, 65, 66].

Energy modelling practices usually apply top-down or bottom-up approaches. A top-down approach uses high-level aggregated information and historical relationships between various macro-economic factors to predict the future behaviour of a system. Bottom-up energy modelling, on the other hand, mainly focuses on the energy system, and the technological changes are the main factors affecting the future forecasts [67].

Depending on different features and particular applicability of the energy models, they could be classified in different categories [32, 35, 68]. In general, in almost all of the energy forecasting models such as TIMES [40-42], MARKAL (MARKet ALlocation) [43-45], RETScreen [46-48] and LEAP (Long range Energy Alternatives Planning System) [69-71]; long-term scenario analysis is used to assess the long-term energy consumption and GHG emissions from the system.

Models such as Global Change Assessment Model (GCAM) and Water Evaluation and Planning (WEAP) use similar approach to assess the long-term water consumption from different sectors and its impacts on the water resources [72-74]. The application of the integrated resource planning models for long-term scenario planning is increasingly attracting attention. Such models integrate different aspects of system development (e.g., economic growth, land use [75], water consumption, atmospheric emissions, and GHG emissions) and also assess the interaction of system development with factors such as changes in atmospheric temperature [76] and availability of water resources [77, 78].

Energy modelling in the industrial sector, to analyze long-term energy efficiency improvement and GHG mitigation, has seen limited use compared to other sectors like the electricity generation, residential, and transportation sectors. This is mainly due to the complexity of the industrial sector, variations in industrial products, and the role of energy carriers both as a source of energy and in some industries as a feedstock [79, 80]. Given the effectiveness of bottom-up energy analyses in other sectors [81-83], however, a technical analysis of industry at the technology level is expected to help address these restrictions. In other words, bottom-up energy modelling and assessing industry performance at both technology and system levels will help to develop comprehensive long-term GHG mitigation strategies in the sector even with the above-mentioned limitations. The current research, therefore, applies energy modeling techniques (i.e., LEAP model) to assess the mid- to long-term energy efficiency and GHG mitigation potential in Canada's industrial sector.

1.1.3. LEAP model

LEAP is an energy policy analysis and GHG mitigation assessment framework [32, 35]. The model is an integrated planning tool that can be used to track the energy flow through all economic sectors including energy consumption, production, and extraction (Figure 1-1). LEAP model is one of the few energy modelling tools with the features to conduct both top-down and bottom-up system analysis [32, 33]. In other words, LEAP is a hybrid model which combines the features of various energy system accounting, evolution and simulation models [35].

Energy modelling in LEAP provides the opportunity to account for the interaction between different modules within the energy system. More specifically, simultaneous consideration of energy supply, transformation, distribution, and demand sectors helps the energy modeler to account for sectoral development and the progress in the energy system at different levels. In addition, the scenario management module in the LEAP model provides the opportunity to analyze individual policy measures and assess different pathways for future energy system evolution [32]. These features provide capabilities to LEAP to analyze the mid- to long- term development of the energy system in different sectors ranging from transportation [84-86] and building [87, 88] on the demand side to electricity generation on the supply side [89-91].

The LEAP model has been extensively used for energy modeling by organizations such as the United Nations Development Programme (UNDP), the United Nations Framework Convention on Climate Change (UNFCCC), the Asia-Pacific Economic Cooperation (APEC), and a number of governmental organizations [92-99]. In fact, LEAP is categorized among the top three most used energy models globally [32].

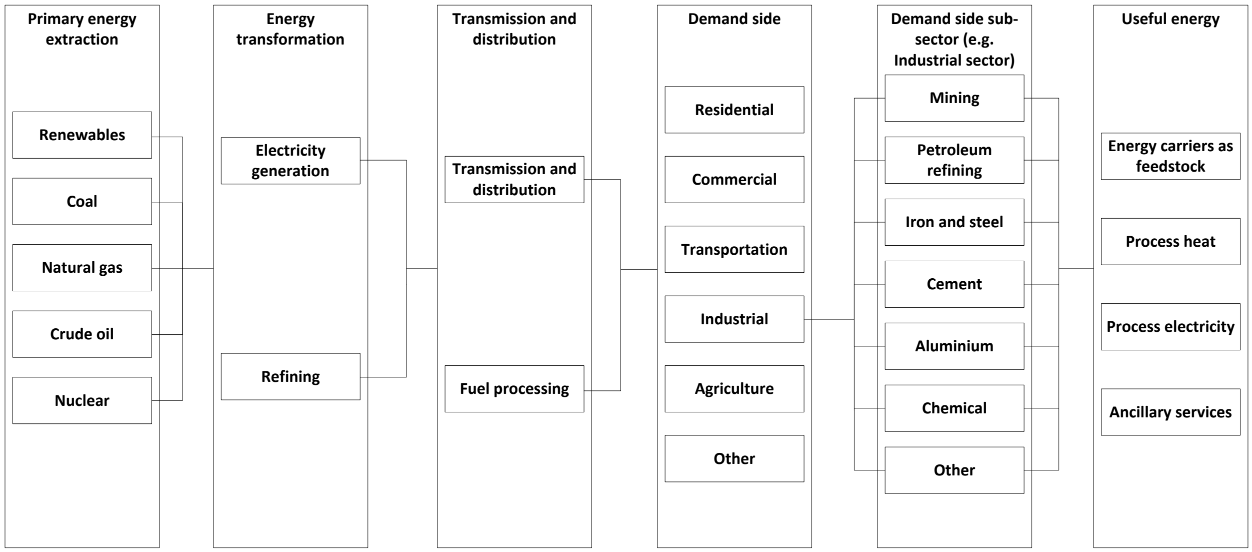

Figure 1-1: Structure of energy system in the LEAP model [79]

LEAP is a bottom-up energy modelling software where aggregating the technology-level energy consumption is used to analyze the overall energy demand in the system. Scenario development in the LEAP model will be used to assess and forecast the growth of the sectoral energy demand, energy transformation, and distribution sectors and ultimately the demand for different types of primary energy. In addition, LEAP has a built-in Technological and Environmental Database (TED) where the detailed environmental impacts of different processes and fuel combustion are available. The TED database can be modified based on the specific characteristics of the process. In other words, the emission factors for energy consumption could be altered depending on the specific process characteristics and also characteristics of the consumed fuel.

1.2. Industrial energy efficiency in Canada

Canada is the 9th largest global GHG emitter [100]. In 2016, the industrial sector was responsible for more than 37% of the national GHG emissions [101, 102]. With the increasing local and foreign demands for Canada's industrial products, the GHG emissions from the sector are expected to almost double by 2050 [65]. That said, the International Energy Agency (IEA)'s recent study highlights that compared to the 2016 level, a 12% energy saving may be realized from Canada's industrial sector by 2050 [103]. In order to reach this potential and to help Canada achieve its international emissions reduction commitments [104] while maintaining the global economic competitiveness of its trade-exposed industries [105], there is an urgent need for industrial energy efficiency improvement. The first step for effective energy efficiency improvement and GHG management in the sector is to identify major energy consumers and measure their GHG emissions, and the next step is to develop GHG mitigation strategies.

In terms of energy and GHG data management, Canada has had systematic and comprehensive energy and environmental databases since 1990 both at national and provincial levels. These are from Natural Resources Canada's Office of Energy Efficiency [106], Statistics Canada [107], and the National Energy Board [108], which provide comprehensive data on the historical and current status of energy flow at both energy supply and demand sides. These data are supplemented by information and databases from research institutions such as the Canadian Energy and Emissions Data Center (CEEDC) [109] and international bodies in which Canada is a member (e.g., Energy Statistics of OECD Countries [110]). In addition, several studies have been conducted to identify the industrial sources of GHG emissions, analyze the overall status of Canadian industries, and compare this status with the global average and the world's best practices [111-114].

However, most studies focus on the industry as a whole (vs process-level analysis) and are based on currently existing technologies (vs state-of-the-art and emerging technologies). This is mainly due to the limited information available on the technology or process-level performance as well as on actual long-term energy efficiency and GHG mitigation potential. Therefore, previous studies on the Canadian industrial sector do not provide information on mid- to long-term energy efficiency improvements and GHG mitigation potential in each industry.

After an extensive analysis of the existing databases and literature on Canada's industrial energy efficiency, the following knowledge gaps were identified:

There is a lack of understanding about the dynamics of historical changes and the driving forces of energy efficiency in Canada's industrial sector in existing databases.

The dynamic of energy consumption within industrial sub-sectors and the flow of energy within the system is often overlooked in the existing studies and there is limited knowledge available about the process-level energy use in different industry.

Most of the available literature on Canada's industrial energy efficiency/climate policy focuses either on system-level analysis or assesses process-level performance measures. There is a gap between these two types of studies in that the impacts of process-level energy efficiency improvement on system-level GHG emissions are overlooked.

There is a clear lack of long-term energy and emissions projections for Canada's industrial sector.

To the best of the author's knowledge, none of the existing studies considers the interaction between the energy supply and demand sectors and therefore the impacts of electricity sector decarbonization are disregarded in assessments of the long-term GHG mitigation potential of the industrial sector.

There is limited data available on the cost of GHG emissions reduction for different options for the industrial sector. Hence the economic performance of industrial emissions reduction is subject to uncertainties.

From a climate policy making perspective, these limitations impose high levels of uncertainty on the actual achievable GHG emissions reduction at federal and provincial levels. For example, having no information on the energy and environmental performance of existing technologies imposes uncertainties about achievable improvements through the implementation of efficiency measures. Similarly, the lack of consistent economic indicators for different efficiency measures will result in inconsistent assumptions on the penetration of those options in the system and the ultimate achievable GHG mitigation potential. Therefore, the overall objective of the current research is to eliminate the limitations facing effective climate policy making in Canada's industrial sector.

1.3. Objectives of the research

The current study aims to comprehensively analyze the current status of several Canadian industrial sectors in terms of both energy consumption and GHG emissions and assess the achievable long-term GHG mitigation potential along with their costs in these sectors. The specific objectives are to:

- Analyze the historical trends of industrial GHG emissions in Canada and assess the relative impacts of various technical and economic factors on the observed trends.

- Analyze the current status of the major industrial sector in terms of technological progress, energy consumption, and GHG emissions.
- Identify the major energy-consuming processes in the identified major energy industry and develop an energy consumption demand tree based on each sub-sector's energy intensity.
- Analyze various energy efficiency improvement measures and assess their applicability to Canadian industries.
- Evaluate the long-term energy and GHG emission impacts associated with implementing the identified energy efficiency technologies.
- Evaluate the cost of GHG mitigation associated with implementing the identified energy efficiency technologies.
- Apply the results to develop mid- to long-term carbon abatement cost-curves for different industries.

1.4. Scope and limitation

This thesis focuses on four major energy-consuming manufacturing industries: the chemical (petrochemical and fertilizer industries), iron and steel, petroleum refining, and cement sectors. These industries are chosen based on two criteria: they are a manufacturing industry (i.e., belong to group 31-33 classifications as defined by the North American Industry Classification System (NAICS)[115]) and are responsible for significant portion of the country's energy consumption and GHG emissions. For each sector, the system boundary was defined to cover all the major energy-consuming processes involved in the industry. System boundary selection was also influenced by the availability of the actual aggregated energy consumption data for different sectors.

The current study focuses on GHG mitigation assessment from manufacturing industries through implementing energy efficiency measures, fuel switching, and modification of existing processes. The impacts of those measures or modifications on other air pollutants or on water consumption are beyond the scope of this study.

Operational parameters, such as energy intensity and the applicability of energy efficiency measures, and economic parameters like fuel price, carbon price, and inflation rate are Canada/province-specific. However, the developed framework could be applied to other jurisdictions as long as specific operational and economic parameters are used.

1.5. Outline of the thesis

The thesis is organized in seven chapters and each chapter, except the introduction and conclusion, is an independent paper. Some of these have been published; others have been submitted to peer-reviewed journals for publication. In other words, this thesis is a consolidation of papers and each chapter is intended to be read independently. As a result, some concepts and data are repeated.

Chapter 1 introduces the background, objective, scope, and limitation of the work.

Chapter 2 analyzes the historical trends of GHG emissions from Canada's industrial sector. The impacts of various factors on the overall GHG emission trend were assessed through decomposition analysis.

Chapter 3 investigates the status of the Canadian cement industry in terms of both energy consumption and GHG emissions. The sector's mid- to long-term GHG mitigation potential was analyzed.

Chapter 4 assesses the long-term development of Canada's iron and steel industries. The energy saving and GHG reduction potential of the sector as a result of adopting emerging low energy intensity technologies and energy efficiency improvement in existing technologies were evaluated.

Chapter 5 develops a framework for techno-economic assessment of various GHG mitigation options for Alberta's petroleum refining industries. The long-term energy saving and GHG mitigation from the sector was assessed.

Chapter 6 chapter examines the historical trends and current status of GHG emissions from Alberta's fertilizer and petrochemical industries and analyzes long-term energy efficiency and GHG mitigation potential from the sector.

Error! Reference source not found. summarizes the key findings, provides the main conclusions, and makes recommendations for future work.

Chapter 2 : Analysis of Historical Trends in Canada's Industrial Greenhouse Gas Emissions: An Index Decomposition Analysis[1]

2.1. Introduction

Concerns about climate change have resulted in global agreement on the need for collective action to reduce anthropogenic and human-induced greenhouse gas (GHG) emissions [116]. Stabilizing atmospheric temperature change below 1.5-2℃ requires a 50% reduction in global annual GHG emissions by 2050, achieving net zero emissions by 2055-2080 and net-negative emissions thereafter [5-8]. In 2016, the final energy consumption from the industrial sector reached 115 EJ, more than 60% of which was fossil fuels [117]. This makes the industrial sector responsible for almost 30% of the global GHG emissions [102, 118]

Canada is the 9th biggest contributor to global GHG emissions and its emissions accounted for 1.6% of the global total in 2013 [100]. The industrial sector is responsible for more than 37% of Canada's GHG emissions [101, 102]. In terms of historical trends, GHG emissions from the Canadian industrial sector increased by almost 25% between 1990 and 2015 [106], exceeding the national average (18%) [119]. With increasing local and foreign demands for Canada's industrial products, the GHG emissions from the sector are expected to almost double by 2050 [65]. Hence, action is needed to help Canada achieve its international climate change commitments [104] while maintaining the global economic competitiveness of its trade-exposed industries [105].

In 2016, the Government of Canada established the Pan-Canadian Framework on Clean Growth and Climate Change, aiming to achieve a 30% GHG emissions reduction from all sectors by

[1] A version of this chapter is submitted Journal of Cleaner Production as Talaei A, Gemechu E, Kumar A. "Analysis of historical trends in Canada's industrial greenhouse gas emissions: An index decomposition analysis,", 2019 (submitted)

2030 compared to the level in 2005 [101]. Establishing regulations that enforce the reduction of methane and hydrofluorocarbon emissions, improving the energy efficiency of industrial activities, and promoting new and clean technologies are the three major areas which are considered to ensure GHG emission reduction and attain long-term clean growth in the industrial sector [101]. Although the importance of the industrial sector in GHG mitigation has been recognized [105], there are no comprehensive and quantitative reduction targets set for the sector. An in-depth understanding of the main GHG emissions' driving forces and their dynamics historically are crucial in order to design and implement effective climate change mitigation strategies in Canada's industrial sector.

Because of the complexity of the industrial sector, variations in types of final products, and the role of energy carriers both as sources of energy and as feedstock, it is difficult to extensively analyze the main factors influencing the GHG emissions from the sector [120]. Similar to the global average, GHG emissons from the Canadian industial sector are primarily energy consuption emissions [106]. Energy intensity and type of energy source are the key factors that influence the overall energy-related GHG emission profile of the sector [121]. Understanding the extent to which these factors impact the sector's environmental performance will provide important insights to policy makers on the effectiveness of climate change mitigation strategies in the sector [122, 123]. A thorough study on emission trends and key contributors would also help highlight the hotspot areas where deep GHG emissions reduction potential could be achieved to foster the building of Canada's low-carbon economy in the long-term [124]. Assessments have been conducted from the local to the global level for Shanghai [125], California [126], China [127], Korea [128], Turkey [129], United Kingdom [124] , European

Union [130], the Organisation for Economic Co-operation and Development countries [131], and the world [132].

To the best of the authors' knowledge, there is hardly any study on the Canadian industrial sector. Ang (2005) used decomposition analysis to study the GHG emissions between 1990 and 2000 for selected Canadian industrial sub-sectors [121]. Since 2000, the industrial sector has undergone structural changes, energy composition and efficiency have improved, and different climate change measures have been implemented. This chapter aims to analyse how the changes contributed to Canada's climate change mitigation strategies by implementing the logarithmic mean Divisia index (LMDI) method to the Canadian industrial sector to decompose the historical GHG emissions and evaluate the contribution of different factors in the growing historical GHG emissions trend. This research contributes to the scientific community and to policy makers at both the local and national levels by providing insights on the long-term relationship between industrial GHG emissions and key factors from technology performance and the energy intensity of industrial processes to macro-economic factors such as economic output of the industry. The study covers a long time frame, from 1990-2014, which allows us to capture gradual changes in industry, a sector known to be capital-intensive and resistant to change [105]. Unlike Ang's study, which focuses on selected industrial sub-sectors [121], this study offers a comprehensive assessment by including all industrial sub-sectors. The specific objectives are:

- To analyze the historical trends of GHG emissions from Canadian industrial sectors and sub-sectors,
- To identify the key driving factors and quantify their relative contributions to the overall GHG emissions trends,

- To highlight the future policy implications of the findings from the historical derivers of the historical GHG emissions trends , and
- To provide relevant information that enhances the development and implementation of effective GHG emissions reduction policies to meet the Pan-Canadian Framework on Clean Growth and Climate Change targets.

2.2. Method

Decomposition analysis is used to analyze the historical trends and driving forces of industrial GHG emissions in the time period between 1990 and 2014. In general, the main purpose of a decomposition analysis is to disaggregate a composite result to a number of pre-defined factors that impact the aggregate through a governing function [121]. There are different decomposition techniques, such as principle component analysis, multivariate linear regression modelling [133-137], and environmentally extended input-output based structural decomposition analysis [138-141].

The Laspeyres index and Divisia index decomposition analysis are the two commonly used methods for energy and environmental decomposition analysis both in academic research and in policy-making processes [122, 141, 142]. Their simplicity and flexibility, theoretical superiority, data availability, and quality are among the key advantages over the other methods [122, 143]. The LMDI method is a preferred method as it results in zero residual when considering specific factors for decomposing energy consumption and GHG emissions [144].

Decomposition analysis based on the Laspeyres index allows us to evaluate the impacts of one factor on the aggregate regardless of changes in the other factors (i.e., all the other factors remain constant), while in Divisia decomposition, all the factors change simultaneously. Decomposition analysis of energy consumption and GHG emissions could be performed for various scopes: from single sector, i.e., residential [145], electricity sector [146, 147], transportation [148, 149], cement [150-152], iron and steel [153-155], textile [156], and metallurgy [157], to economy-wide analysis [158-165]. Many studies in the literature, however, focus on the sub-sectors of an industry (e.g., a sub-sector of the manufacturing sector [166] or the manufacturing sector as a whole [129, 167]). Because of the complexity and interconnected nature of industrial subsectors and the diversity of their products [80], decomposition studies focusing on the entire industrial sector are relatively limited [168, 169].

2.2.1. Decomposition analysis

In this study, the Divisia decomposition method is implemented to analyze the change in overall GHG emissions from the Canadian industrial sector. In keeping with factors used in previous studies in in the literature, the following are used for decomposition analysis: activity level, energy intensity, structural change of the industry, fuel mix, and emissions factor [128, 129, 170]. A simplified scheme describing the interaction of each factor to induce changes in GHG emissions is shown in Figure 2-1.

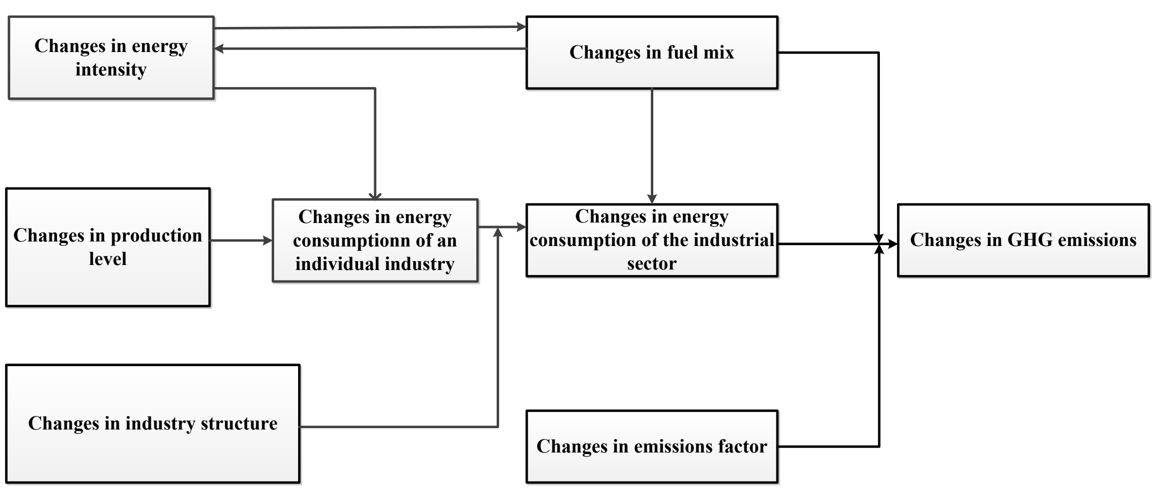

Figure 2-1: Factors affecting the overall GHG emissions from the industrial sector

As shown in Figure 2-1, an individual industry's energy consumption is mainly driven by changes in energy intensity and production level. These, together with the changes in the structure of the industrial sector (i.e., the share of individual industries in the overall industrial sector's output), affect overall industrial energy consumption in the sector. In addition, because of the variation in the heating value of different fuels, the fuel mix affects the overall energy consumption indirectly. Overall, the total emissions from the industrial sector (consisting of "i" sub-sectors and consuming "j" type of fuels) can be described by Equation 2-1 [121]:

$$C = \sum_{ij} C_{ij} = \sum_{ij} AC \frac{AC_i}{AC} \frac{E_i}{AC_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_{i} AC * ST_i * EI_i * FM_{ij} * EF_{ij} \quad \textbf{Equation 2-1}$$

where C is the total aggregated GHG emissions from the entire sector, C_{ij} is the GHG emissions from industry "i" associated with the consumption of fuel "j", AC is the sectoral activity (i.e., total dollar output from industry CAD), ST_i or ($\frac{AC_i}{AC}$) represents the structure of the industrial sector (i.e., share of industry "i" in the total industrial output), EI_i or ($\frac{E_i}{AC_i}$) is the energy intensity of the industry "i", which reflects the total energy requirement per dollar output (GJ/CAD), FM_{ij} or ($\frac{E_{ij}}{E_i}$) is the fuel mix of the industry "i", which shows the share of fuel "j" in the total basket of fuels consumed in industry "i", and EF_{ij}or ($\frac{C_{ij}}{E_{ij}}$) is the GHG emission intensity as emissions per unit of energy carrier "j" consumed in industry "i" (kg CO_2eq/GJ).

Due to the variety of industrial outputs and to maintain consistency, it is a widespread practice to harmonize the output, i.e., by using the economic output of the industry as the activity indicator [171]. In this study, the overall industrial gross domestic product (GDP) is considered the output (CAD). Therefore, the structure of the industrial sector is determined by considering the share of individual industries in the overall industrial output (i.e., CAD_i/CAD_{total}, where "i" represents the individual industry). The energy intensity reflects the total energy requirement per dollar output (GJ/CAD) and the emission factor shows the amount of GHG emissions per unit of energy consumption of that specific fuel (kg CO_2eq/GJ). Equation 2-2 expresses the governing function used for the decomposition analysis [121].

$$\Delta C_{TOT} = C^{T} - C^{0} = \Delta C_{AC} + \Delta C_{ST} + \Delta C_{EI} + \Delta C_{FM} + \Delta C_{EF}$$ **Equation 2-2**

In Equation 2-2, ΔC_{TOT} is the overall change in the industrial GHG emissions between the base year "0" and the end year "T". The contributions of industrial activity, structure of the industry, energy intensity, fuel mix, and emission factor are denoted by ΔC_{AC}, ΔC_{ST}, ΔC_{EI}, ΔC_{FM}, and ΔC_{EF}, respectively. Table 2-1 provides a brief description of each factor.

Table 2-1: Description of the factors (considered in the decomposition analysis)

Factor	Abr.	Description	Index/Unit
Activity level	AC	This refers to the production level as gross domestic output of the sector as a whole.	GDP-Million $2007 per year
Industry structure	ST	This factor shows the impacts of structural change (i.e., the shift from energy-intensive industries toward less energy-intense industries) as it captures the share of different industrial sub-sectors in the overall structure of a given industry. This is different from energy intensity improvement, which occurs in a single industry.	Ratio of industry "i" output to the overall industrial sector output ($\$_i/\Sigma_i\$_i$)
Energy intensity	EI	This shows the effective use of energy to produce final products.	Energy consumption per dollar output of final products (GJ/$)

Factor	Abr.	Description	Index/Unit
Fuel Mix	FM	This reflects the impacts of the carbon content of different fuels consumed to produce final products.	Share of different fuels in overall fuel consumption (GJ_{ij}/GJ_i)
Emission factor	EF	While the emission factor of fuel combustion is constant, the environmental mitigation technologies/standards vary in various industries. The emission factor also includes the emission factors of the electricity grid.	Kg $CO_2eq.$/GJ

Equation 2-2 is further broken down to show how each factor is calculated (i.e., Equation 2-3 to Equation 2-7) [121]:

$$\Delta C_{AC} = \sum_i \frac{C_{ij}^T - C_{ij}^0}{lnC_{ij}^T - lnC_{ij}^0} \ln \frac{AC^T}{AC^0}$$ **Equation 2-3**

$$\Delta C_{ST} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{lnC_{ij}^T - lnC_{ij}^0} \ln \frac{ST_i^T}{ST_i^0}$$ **Equation 2-4**

$$\Delta C_{EI} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{lnC_{ij}^T - lnC_{ij}^0} \ln \frac{EI_i^T}{EI_i^0}$$ **Equation 2-5**

$$\Delta C_{FM} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{lnC_{ij}^T - lnC_{ij}^0} \ln \frac{FM_{ij}^T}{FM_{ij}^0}$$ **Equation 2-6**

$$\Delta C_{EF} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{lnC_{ij}^T - lnC_{ij}^0} \ln \frac{EF_{ij}^T}{EF_{ij}^0}$$ **Equation 2-7**

As above, in Equation 2-3 to Equation 2-7, “i” and “j” refer to industry and fuel type, respectively. The decomposition model was developed in Matlab. In practice we replaced all the zero values in the dataset that we developed by 10^{-10} to avoid ln (0) [121]. The decomposition model for the analysis is provided in Appendix I-I.

2.2.2. Data

The time period between 1990 and 2014 was considered in the analysis. 2014 is the latest year for which official data on energy consumption and GHG emissions are publicly available. The long time period makes it possible to account for factors such as the longer lifetime of industrial technologies (compared to the residential, commercial, and transportation sectors, where technologies have shorter lifetimes) and the relatively slow turnover rate of the existing technologies in the sector.

The analysis in this study covers the full spectrum of the Canadian manufacturing and non-manufacturing industrial sector based on the North American Industry Classification System (NAICS) categorization [172]. Cement, chemical, construction, forestry, iron and steel, mining, petroleum refining, pulp and paper, and smelting and refining cumulatively account for 87% of the overall energy consumption and 82% of the total GHG emissions from the Canadian industrial sector [106]. The remaining industries are all grouped as “other manufacturing,” which includes textile, electronics, computers, and food industries, among others.

Table 2-2 provides a brief description of the main industries considered.

Table 2-2: Industrial sub-sectors [172]

Industrial sub-sector	NAICS #	Sector/sub-sector activities
Construction	23	Land development, construction, repair and renovation of buildings, and heavy construction.
Paper manufacturing	322	Manufacturing of pulp, paper, and paper products.
Non-ferrous metal (except aluminum) smelting and refining	33141	Smelting and refining of non-ferrous metals (except aluminum), including the onsite forming and finishing of final products.
Petroleum and coal product manufacturing	3241	Refining and transformation of crude oil and coal to end-use products (mainly occurs in petroleum refining).
Cement manufacturing	32731	Production of hydraulic cement and various concrete products.
Chemical manufacturing	325	The processing of organic and inorganic raw materials and production of final chemical products.
Iron and steel mills and ferro-alloy manufacturing	3311	Processing raw materials including iron ore and steel scrap; and the production of molten iron, steel, and finished products (e.g., plates).
Forestry and logging	113	The growing and harvesting of timber along production cycles (greater than 10 years).
Mining, quarrying , and oil and gas extraction	21	Extraction of primary fuels such as crude oil, natural gas, and coal, including quarrying, well operations, and milling.
Other manufacturing	NA	All other industrial sub-sectors including metal mining, salt mining, potash mining, textile industries, motor vehicle industries, electronic equipment manufacturing, furniture industries, etc.

The following fuel types were examined in the assessment: electricity, natural gas, liquefied petroleum gases and liquefied natural gas, coal, coke, coke oven gases, heavy fuel oil, diesel fuel oil, light fuel oil and kerosene, petroleum coke and distilled gases and wood waste and pulping liquor.

Five data classes were used to develop the decomposition model and analyze the historical GHG emission trends: the annual output of each industry (i.e., industrial activity), the share of each industry in the overall output (industry structure), the fuel consumption, type of fuel, and the corresponding fuel emission intensities. The data was mainly acquired from official governmental databases such as Natural Resources Canada (for sectoral energy consumption and GHG emissions) [106, 173], Statistics Canada (for industrial output and activity level) [107], and the Canadian Energy and Emissions Data Centre (used to supplement the NRCan database for industry-specific energy consumption and GHG emissions) [174]. The data on historical energy consumption (by industry and fuel type), GHG emissions (by industry and fuel type) and activity level (by industry) are provided in Appendix I-II.

Analysis of the historical data shows that from 1990 to 2014, the GHG emissions from Canada's industrial sector increased by more than 25%. More specifically, there is a continuously increasing trend in industrial GHG emissions except for the years 2008 and 2009, during the global economic crisis that slowed industrial activities (Figure 2-2) [106]. In 2014, the mining sector, with a share of more than 45% of overall emissions, was the biggest contributor to both energy consumption and GHG emissions in the industrial sector. Petroleum refining, iron and steel, and the chemical sectors followed with shares of 10.7%, 8.9%, and 7.3% of total industrial emissions, respectively.

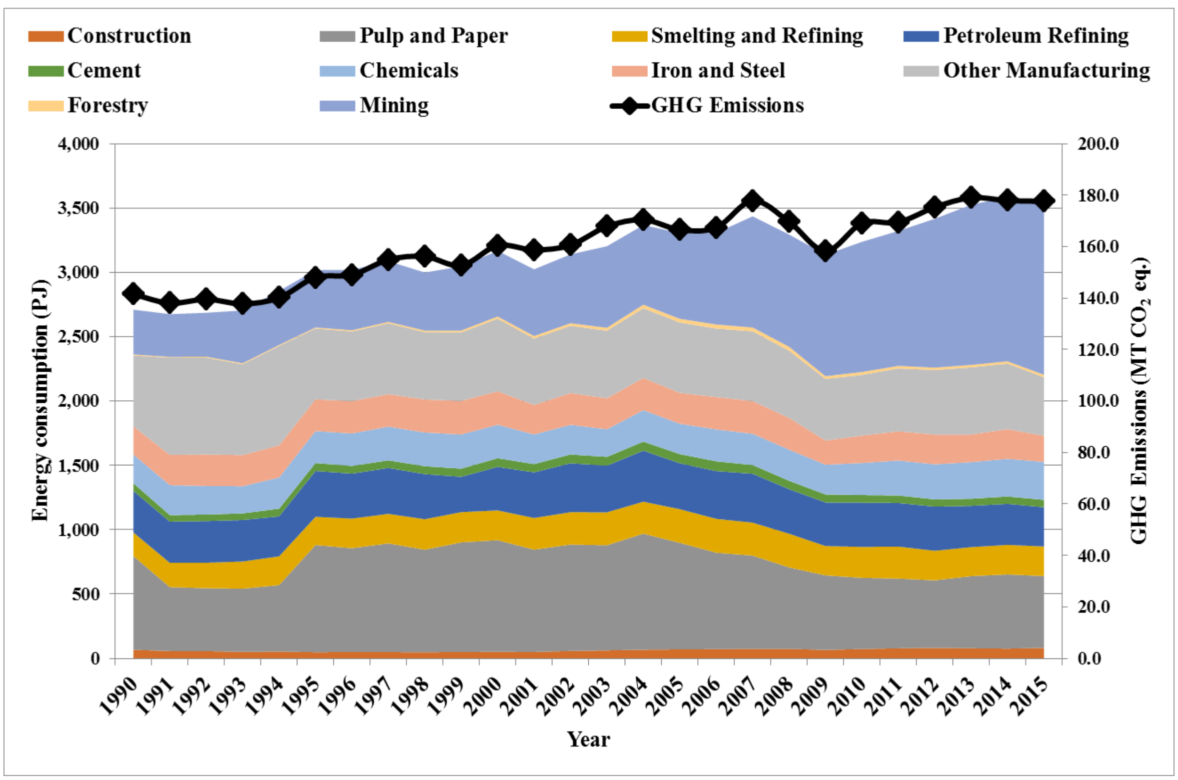

Figure 2-2: Historical energy consumption and GHG emissions in Canada's industrial sector [106]

On an aggregated basis, as shown in Figure 2-2, there is a direct relationship between total energy consumption and GHG emissions trends. GHG emissions increase in proportion with changes in overall energy consumption. However, by sector, energy consumption and associated GHG emission contributions differ because of various factors, such as change in fuel type and associated emission factor.

Table 2-3 provides some insights on the variations in energy and GHG emissions for different sectors.

Table 2-3: Energy consumption and GHG emissions in different industrial sub-sectors [106]

Industrial sub-sector	Energy Consumption			GHG Emissions		
	1990 (PJ)	2014 (PJ)	Change	1990 (Mt)	2014 (Mt)	Change
Industry Total	2,710.0	3,584.4	32%	141.5	177.9	26%
Construction	66.9	76.5	14%	4.3	5.1	19%
Pulp and paper	728.2	576.4	-21%	24.5	9.9	-60%
Smelting and refining	183.3	229.3	25%	10.9	9.5	-13%
Petroleum refining	323.3	319	-1%	18.2	18.9	4%
Cement	59.3	57.7	-3%	4.4	4.3	-2%
Chemicals	223.2	292.4	31%	10.9	13	19%
Iron and steel	219.4	231	5%	16.5	15.8	-4%
Forestry	7.7	18.4	139%	0.6	1.4	133%
Mining	347.6	1,275.8	267%	22.5	80.5	258%
Other manufacturing	551.1	408.5	-26%	28.7	19.5	-32%

Table 2-3 suggests that in some of the industrial sub-sectors such as cement, chemical, and construction, energy consumption and GHG emissions follow the same trend. In other sub-sectors such as forestry, iron and steel, mining, petroleum refining, and pulp and paper, although energy consumption and GHG emissions follow the same trend (i.e., in these sectors, while an increase and decrease in energy consumption and GHG emissions follow the same trend, their rate of change is not correlated to each other), there is no obvious correlation between the two factors. In other sectors, changes in energy consumption and GHG emissions trends are not the same. For example, in the smelting and refining, the energy consumption increased by 20% between 1990 and 2014, while overall GHG emissions decreased by 14%.

This lack of correlation highlights the fact that besides gross energy consumption, factors such as fuel type and emissions factor affect system-level GHG emissions, and that emphasizes the importance of decomposition analysis in identifying the impacts of different factors when comparing energy consumption and GHG emissions trends at sector or sub-sector levels.

2.3. Results and discussion

2.3.1. Decomposition analysis

Figure 2-3 shows the results of decomposition analysis. These were calculated based on the Equation 2-3 to Equation 2-7. The bars represent the impacts of individual factors on overall GHG emissions and the line shows the aggregated impacts of all the factors. All the data in Figure 2-3 are relative to the 1990 baseline. The positive values indicate an increase in GHG emissions and the negative values are interpreted as GHG emissions reduction. While the results of decomposition analysis are shown in Figure 2-3, in the following section we analyzed the changes in the driving forces and interpreted how they impacted the overall industrial GHG emissions.

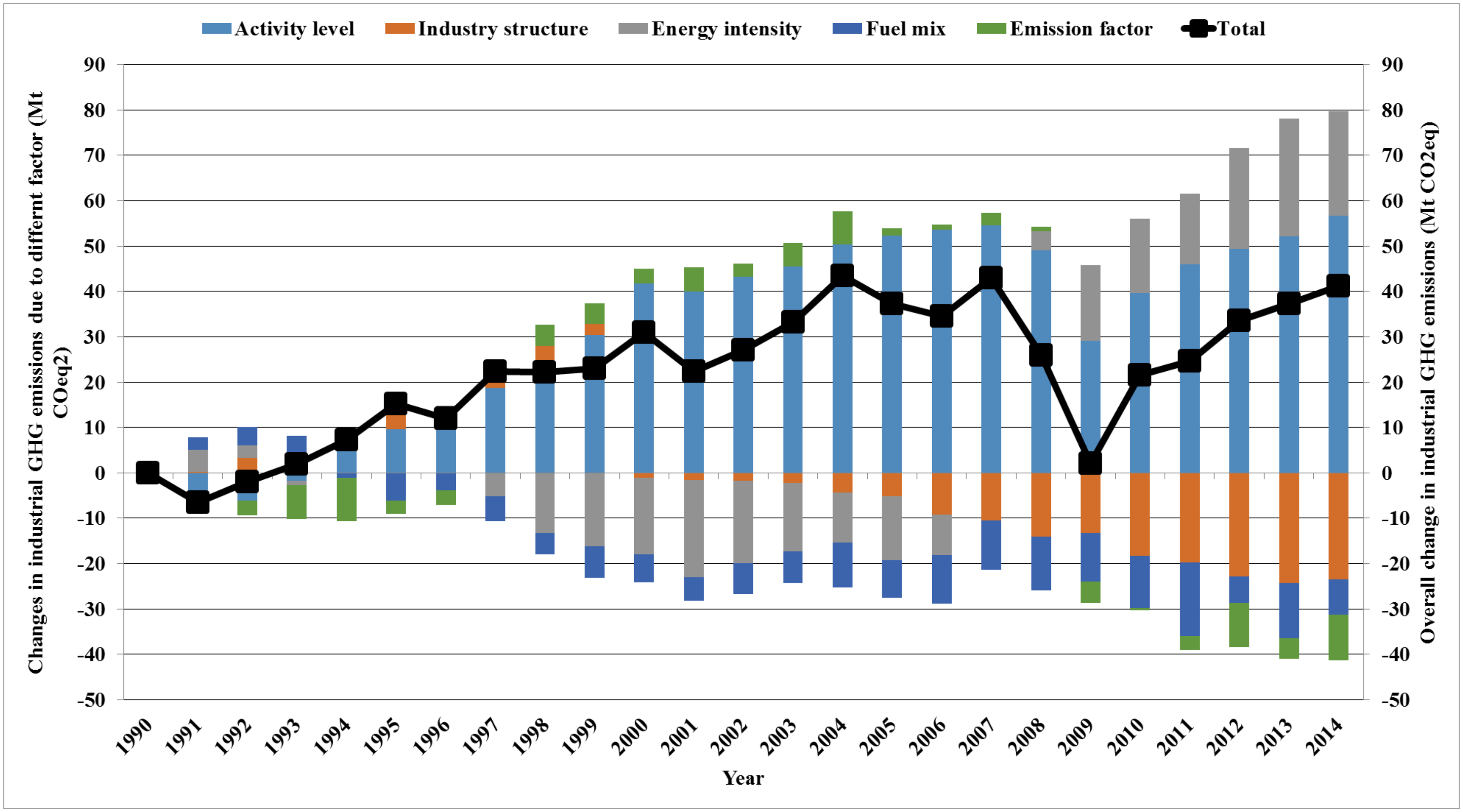

Figure 2-3: Results of decomposition analysis

2.3.2. Activity level and structure of the industry

The activity level of the industrial sector appears to be the main driver for the increasing GHG emissions. The total production level of Canada's industries has continuously increased from CAD 291 M in 1990 to CAD 432 M in 2014 [106, 107]. Despite slight changes over time, the construction and mining sectors remain the main contributors to industrial output in Canada. The Canadian construction sector consists of three sub-sectors, residential building, non-residential, and engineering, cumulatively accounting for 7% of Canada's GDP in 2017 [175]. While the economic output of the construction industry has shown continuous increase from 72,696 million CAD in 1990 to 121,668 million CAD in 2014, the share of the construction sector in overall industrial GDP has fluctuated between 20% and 30% over the years.

The mining sector is one of the fastest growing industrial sectors in Canada. The sector's economic output increased from 83,399 million CAD in 1990 to 132,193 million CAD (Table A-5 in the Appendix I-II) in 2014 (i.e., 60%). The mining sector's contribution to overall industrial sector output has been almost constant (fluctuating between 29% and 31%). Historically, the mining and construction sectors have made up 50 - 60% of the industrial sector's economic output [106, 107].

Other sub-sectors such as cement, chemical, iron and steel, and petroleum refining have shown positive GDP growth, though their shares in overall industrial output are relatively small. For example, the GDP from smelting and refining increased by 84%, but its overall contribution is less than 2% (Table A-5 in the Appendix I-II). Only the pulp and paper and forestry sector outputs decreased between 1990 and 2014 (-15% and -7%, respectively). This is mainly because of the changes in the US market (one of Canada's main pulp and paper import partners) and the increases in market competitiveness as a result of globalization [176].

As seen in Figure 2-3, the impacts of industry structure were positive during the initial years of the analysis (i.e., until 1999). However, in later years, a shift toward less carbon-intensive industries is observed. More precisely, since 2000, the impact of industry structure on overall GHG emissions was not only negative but increasingly negative. This is mainly a result of the increasing share of construction industries in overall industrial output.

Broadly speaking, our results suggest that while the activity level of different industrial sub-sectors is a decisive factor affecting the overall emissions from the sector, the industries with the highest activity level are not necessarily those with the highest GHG emissions. For example, while the construction industry made up almost 30% of the industrial output, its share in the sector's overall GHG emissions was only 2% - 3% of industrial GHG emissions. This is because of the relatively lower emission intensity of the construction sector compared to other sectors (i.e., 0.042 ktonne CO_2eq/\$2007 vs. 0.606 ktonne CO_2eq/\$2007 for the mining sector).

2.3.3. Fuel mix

Since 1994, fuel switching and extended use of low-carbon fossil fuels has resulted in decreasing overall industrial GHG emissions. Between 1990 and 2014, there was an obvious shift toward the use of low-carbon fuels in Canadian industries. Since 1990, the consumption of heavy fuel oil (HFO), coal, and coke (i.e., carbon-intensive fuels) have decreased by 80%, 12% and 21%, respectively [106, 174].

Several environmental policies and regulations from the federal and provincial governments on fuel use and emission reduction have helped fuel switching in Canadian industries. Examples of facility-level GHG emissions regulations and standards include Quebec's Clean Air Regulations (Environmental Regulatory Act), which aims to establish particle and gas emissions standards, air quality standards, etc. [177], and the Government of Manitoba's 2011 Emissions Tax on Coal and Petroleum Coke Act, a tax for individuals and companies who consume more than one tonne of coal or petroleum coke annually [178].

Sectoral and economy-wide regulatory measures and legislations include the Government of Alberta's 2007 Specified Gas Emitters Regulation for large industrial facilities in Alberta, which set pre-defined GHG emission limits [179]. That same year, the Government of Quebec imposed a carbon tax on fuel use. This program was expanded in 2013, when Quebec and California formed a joint carbon market wherein industries in each jurisdiction are allowed to buy carbon offsets from each other [180]. British Columbia has had a carbon tax system since 2008 [181].

In order to avoid the extra costs imposed by these regulations, industrial stakeholders are incentivized to adopt low-emissions fuels. In addition, financial measures provided by energy suppliers (e.g., interruptible contracts) have facilitated the shift toward the use of lower-carbon fuels by industries such as pulp and paper [182] and cement [183]. This has resulted in a relatively large share of low-carbon fuels in the industrial energy consumption fuel mix. More specifically, in 2014 more than 86% of the final energy consumption in Canadian industries was dominated by relatively low-carbon fuels such as natural gas (41%), electricity (20%), still gas (13%), and wood waste (12%), an increase from the 1990 cumulative share of low-carbon fuels of 79% [106, 174]. Overall, analysis of historical data indicates that fuel switching and the use of less carbon-intense fuels has continuously taken place in Canadian industries, and high-carbon fuels (i.e., diesel, heavy fuel oil, coal, LPG, coke, and coke oven gas) accounted for less than 14% of the sector's energy consumption in 2014.

2.3.4. Energy intensity

The impact of industrial economic-energy-intensity (energy consumption per unit of economic output) on overall GHG emissions has varied. That is, while economic-energy-intensity improvement helped reduce sectoral GHG emissions between 1997 and 2006, it led to an increase in the emissions since then [182]. The sudden change (from negative to positive) in the impact of energy efficiency on overall industrial GHG emissions occurred in 2008 and was mainly due to the 13.2% reduction in industrial output that year as a result of the global economic crisis. In the same year, overall industrial energy consumption increased by 10%. The two factors together led to a 56% increase in industrial energy intensity.

The overall economic-energy-intensity of industry improved by almost 11% (i.e., from 9.3 to 8.3 MJ/$2007-GDP in 1990 and 2014, respectively), yet the trend is not consistent among industrial sub-sectors [106]. The economic-energy-intensity of the industrial processes varies considerably (Figure 2-4).

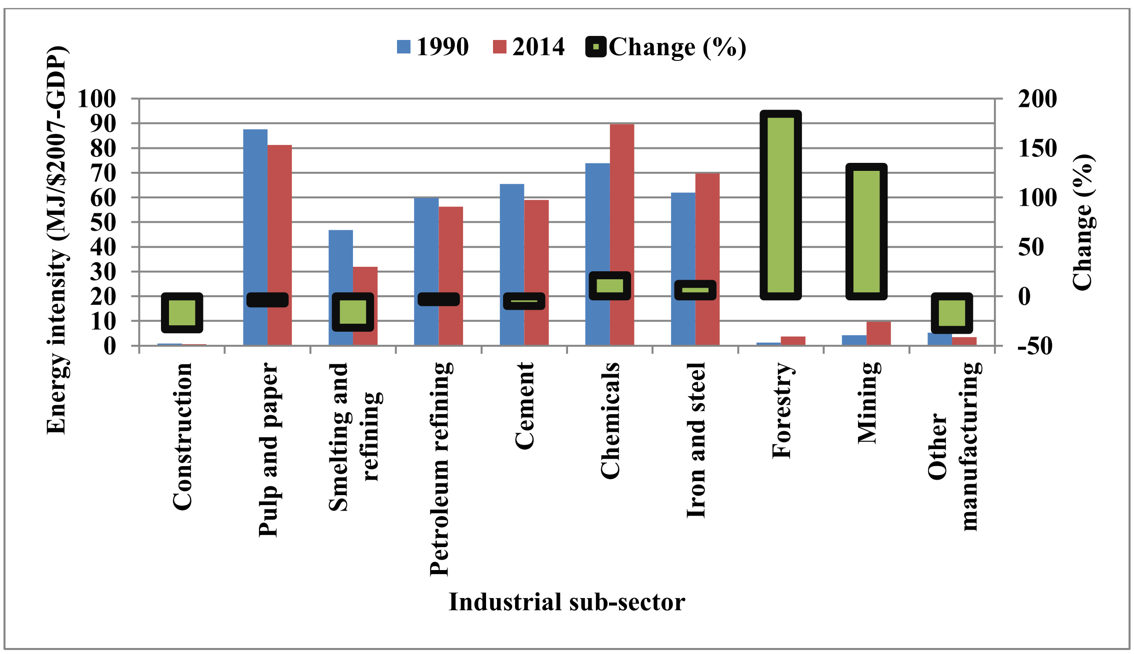

Figure 2-4: Changes in economic-energy-intensity among industrial sub-sectors [106]

The economic-energy-intensities of construction, pulp and paper, smelting and refining, petroleum refining, cement, and other manufacturing have decreased, while the mining, forestry, iron and steel, and chemical sectors have increased. The economic-energy-intensities of construction and smelting and refining industries have improved significantly, by 33% and 32%, respectively. Forestry and mining showed the biggest increases, i.e., 185% and 131%, respectively.

The energy consumption per unit economic output product (i.e., economic-energy-intensity) in the forestry and construction sectors is only a fraction of the industry average. Therefore, even big changes (by percentage) in these sub-sectors are expected to have minimal impacts on overall industrial energy consumption and GHG emissions compared to high energy-intensive industries such as mining, even though the sector might have similar economic output [184].

The main contributor to the increasing industrial economic-energy-intensity is the mining sector, in which the shift toward more energy-intensive extraction technology from surface mining (with a process-energy-intensity of 63.22-88.76 MJ/GJ of bitumen) to steam-assisted gravity drainage (SAGD) (with a process-energy-intensity of 128.32-422.20 MJ/GJ of bitumen) was the main driver [185]. While oil sands production has grown from 343 thousand barrels per day in 1990 to 2163 thousand barrels per day in 2014, the share of oil sands extraction using SAGD technology increased from 39% to 54% during the same time period [186].

When considering process-level energy consumption, while energy is consumed for lighting, industrial transportation, etc., most industrial energy consumption is the fuel for heat generation (75% of the total) and in motor systems (e.g., compressors, fans, and pumps) [184]. For both major energy-consuming categories, several regulatory measures have resulted in energy efficiency improvement between 1990 and 2014. These programs range from awareness raising (information campaigns) to regulatory standards and rebates for energy management and retrofits

[187]. Historically, these programs have been in place (at the federal and provincial levels) to help industries improve their energy efficiency and increase their level of competitiveness and profitability [188]. For example, NRCan provides financial incentives to industries to implement ISO 50001 Energy Management System Standard, Energy Management Information System projects, and Process Integration and Computational Fluid Dynamics studies [189]. Through the ENERGY STAR Challenge for Industry program, NRCan incentivizes industries to reduce their facilities' energy consumption by 10% over a 5-year period [190]. By improving energy efficiency, these programs have helped several industries reduce their operating costs and improve their productivity and environmental performance [191].

2.3.5. Emissions factor

Except the decade between 1998 and 2008, when the GHG emission factor (EF) contributed to the increase in industrial GHG emissions, for the rest of the study period, the GHG emissions factor helped lower GHG emissions from the industrial sector. The GHG emissions factors from both fuel combustion and electricity generation have changed over time. While the combustion EF is the result of improvement in fuel grades and the implementation of GHG emissions reduction technology at combustion facilities, the electricity generation EF is mainly due to the decarbonizing of the electricity supply sector. The GHG emissions factor from fossil fuel combustion is considered to be unchanged.

Of all the fuels used in Canada's industrial sector, coal and coke/coke oven gas have the highest GHG emissions factors, followed by heavy fuel oil and diesel fuel oil. The combustion of wood and wood products has the lowest GHG emissions factor of almost zero. This is because of the fact that biofuels are considered to be carbon neutral (i.e., the emissions from biofuel combustion equals to the amount that the plants absorb while growing) and there is a negligible amount of emissions associated with its transportation and processing [192, 193]. Analysis of the historical data confirms that the GHG emission factors from the combustion of different fuels have not changed noticeably over time; they have remained constant [106].

Compared to fossil fuels, electricity is often considered a cleaner energy source as it has no GHG emissions at the point of consumption. However, when life cycle emissions (i.e., electricity generation, transmission, distribution, and consumption) are considered, there is an environmental footprint associated with electricity generation. Historically, in Canada, the fossil fuels used for electricity generation are coal, natural gas, and heavy fuel oil. Between 1990 and 2014, electricity generation in Canada has increased from 468 TWh to 638 TWh (i.e., 36.5%). In this period, while electricity generation from low-carbon fuels has increased, electricity generation from coal, petroleum coke, and heavy fuel oil has decreased, mainly as the result of environmental regulations at federal and provincial levels. This has resulted in decarbonization of the electricity supply sector. More specifically, between 1990 and 2014, GHG intensity in terms of tonne CO_2eq/TJ electricity generated decreased by 24.4% [173].

The only exception to this trend is the years 1998-2008. In the 2000s, the Government of Ontario set an initial timeline for a coal phase-out (initially for 2007 and then postponed to 2014). In order to address concerns about the reliability of electricity supply in the absence of coal, several nuclear plants underwent early maintenance and were taken offline (while the coal plants were still operating) [194, 195]. This resulted in an increase in the average GHG emissions factor from the electricity sector in that time period. The emissions factor fell when nuclear plants came online again and coal power plants were phased out (Figure 2-5).

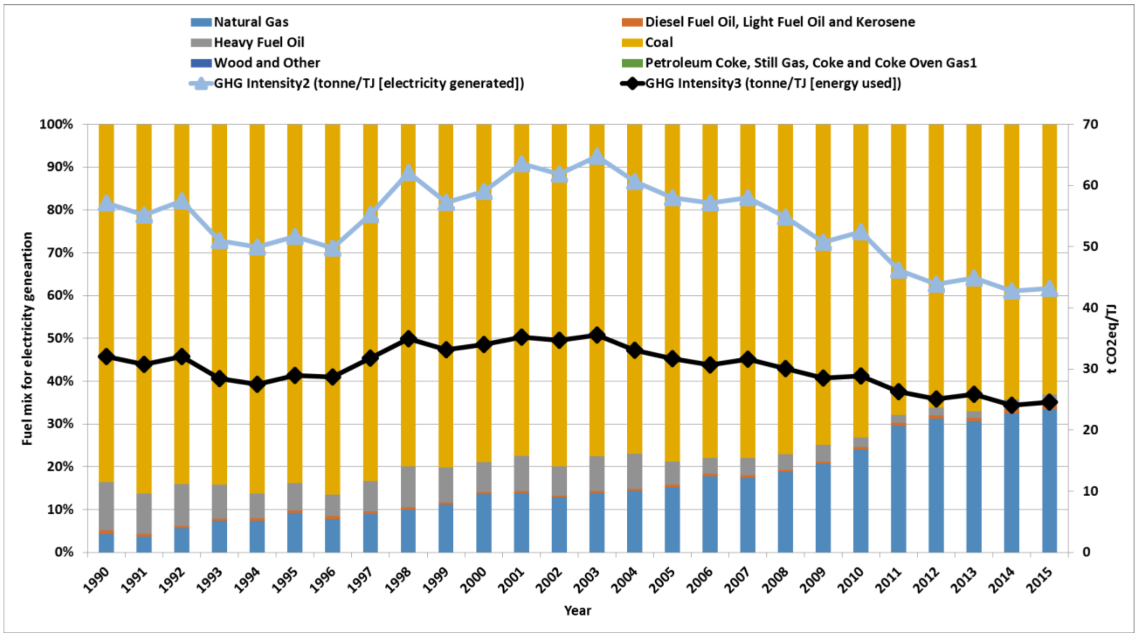

Figure 2-5: Carbon intensity of electricity generation in Canada[2] [173]

2.3.6. The dynamics of the driving forces

The results in Figure 2-6 highlight the fluctuating impacts of individual factors on industrial sector GHG emissions overall. Figure 2-6 shows changes during different time periods (1990-1994, 1995-1999, 2000-2004, 2005-2009, and 2010-2014). The impacts of each key factor are compared to the initial year of the sub-period. For example, the year 1995 used to analyze the changes between 1995 and 1999. Each line in the graph shows the changes in different factors in a specific time period.

[2] Excludes hydro and nuclear

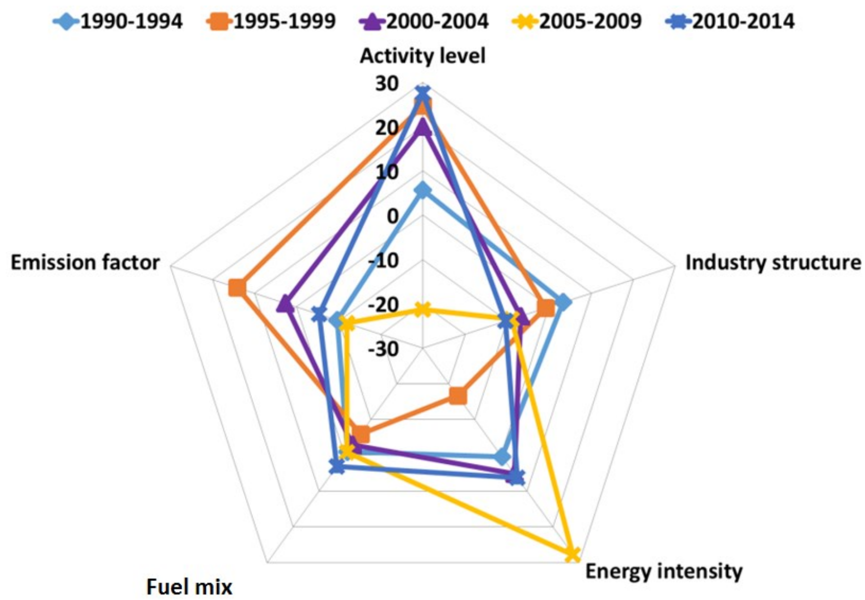

Figure 2-6: Impacts of individual factors on overall industrial GHG emissions

In every sub-period, activity level has the biggest impact on industrial GHG emissions. The impacts were relatively high in 2010-2014, 1995-1999, and 2000-2004 and low in 2005-2009 during the global economic crisis. In general, energy intensity has two components, constant and variable energy consumption. The former is uniform for industry regardless of the activity level and the latter is proportional to the activity level. Increasing the utilization factor (i.e., proportion of the nominal production capacity used for production) of the industry reduces the energy intensity of the industry. In other words, by increasing the utilization factor, the numerator of the energy intensity equation ($\frac{constant\ energy\ use + variable\ energy\ use}{total\ producion}$) increases less than the denominator and therefore the overall energy intensity decreases accordingly. The global economic crisis resulted in a decrease in Canada's industry utilization factor and therefore increased the energy intensity [196]. The trend reversed after 2010 [182].

The contribution of energy intensity to overall industrial GHG emissions was the highest during between 2004-2009 (i.e., the GJ/GDP denominator decreased dramatically, leading to an increase in the contribution of energy intensity). In fact, except for the years 1995 and 1999, the changes in energy intensity led to an increase in overall industrial sector emissions. This means that the energy consumption reduction rate has been slower than the economic growth rate in Canada's industrial sector.

The role of industry structure in GHG emissions reduction from the sector has continuously increased. The shift toward low-carbon industries not only has helped GHG emissions reduction in the sector (except between 1990 and 1994) but its impacts are becoming more substantial (i.e., the impacts on GHG emissions reduction in consecutive time periods are higher).

Similarly, during most of the time period of the study, the fuel mix helped reduce industrial sector GHG emissions. After 2009, however, changes in the fuel mix led to an increase in GHG emissions. These changes were from a 25% increase in LPG and LNG consumption and a 6% increase in coke and coke oven gas consumption. These increases were the result of a 70% increase in activity level in the iron and steel sector, the largest industrial consumer of coke and coke oven gas in Canada.

The GHG emissions factor contributed to the increase in industrial GHG emissions during the years 1995-2004, mainly due to the increase in electricity generation emissions factors [173]. For the rest of the study period, decarbonizing the electricity supply chain indirectly helped reduce industrial sector emissions.

2.3.7. Drivers of change in industrial sub-sectors

Between 1990 and 2014, the aggregated impacts of individual factors show in an overall increase in industrial GHG emissions in Canada, from 141.5 Mt CO_2eq in 1990 to 179.9 Mt CO_2eq in 2014 (i.e., 26%). However, the trend is not consistent among the sub-sectors. Between 1990 and 2014, the pulp and paper, smelting and refining, construction, and iron and steel industries showed considerable environmental improvement (53%, 53%, 29%, and 21% GHG emissions reduction per $ output, respectively). The cement and petroleum refining industries showed moderate improvement, 10% and 1%, respectively. Yet the forestry, mining, and chemical industries showed increasing GHG emissions intensity, and the intensity of these sectors increased by 158%, 126%, and 11%, respectively.

The main drivers of change in the GHG emission intensity of different industrial sub-sectors are summarized in

Table 2-4.

Table 2-4: Drivers of change in GHG emission intensity of different industrial sub-sectors

Industry	Drivers of change in GHG emissions
Cement	• The sector's energy intensity has decreased by 11% (mainly in terms of thermal energy consumption) [197] • The clinker-to-cement ratio decreased from 87% to 80% [197] • Fuel switching and increasing natural gas use helped reduce the GHG intensity of the process mainly after 2011 [198].
Pulp and paper	• Decrease in HFO consumption due to interruptible contracts by fuel suppliers [182] • Decreasing share of natural gas in fuel share from 15.8 to 12.9% [106] • Increasing share of wood fuel from 44.2 to 61.1% [106] • Improved energy intensity from 87.6 to 74.9 MJ/$2007-GDP [106] • More than 50% decrease in newsprint production in the time period of the study [182]
Iron and steel	• Increasing share of electric arc furnaces over basic oxygen furnaces in final steel product production [106, 199]
Smelting and refining	• Increasing share of electricity in the fuel mix from 72.6 to 80.6% [106] • Decrease in energy intensity from 46.8 to 31.9 MJ/$2007-GDP [106] • The increase in aluminum production of almost 90% contributed to an increase of almost 70% in this sector's energy consumption [182]
Construction	• Energy intensity has decreased by 33% [106]
Petroleum refining	• Increasing share of still gas from 61.9% to 72.2% [106] • Decreasing energy intensity from 59.7 to 56.2 MJ/$2007-GDP [106]
Forestry	• Increase in energy intensity by almost 300% from 1.3 to 3.8 MJ/$2007-GDP [106]
Mining	• Increase in energy intensity from 4.2 to 84.2 MJ/$2007-GDP [106] • Reduction in the share of electricity from 29.8% to 8.5% [106] • Increase in the cumulative share of natural gas and still gas from 33.1% to 80% [106] • Reduction in the share of high-carbon fuels such as coal, coke, LPG, and diesel fuel oil [106]
Chemical	• Decrease in the share of electricity from 29.4% to 23.7% [106] • Increase in the share of natural gas from 59.7% to 70.6% [106] • Increase in energy intensity from 73.9% to 92.2% [106]

As shown in the table, the drivers of change in sectoral GHG emissions differ from one sub-sector to the next. For example, in the mining sector, both the increase in activity level and the shift toward the extraction of unconventional oil are the main drivers of the sector's increase in GHG emissions. In the pulp and paper industry, the main drivers are the decrease in activity level (i.e., newsprint production) as well as fuel switching (resulting from favorable regulations around low-carbon fuels). In petroleum refining, the increase in utilization rate improved the energy intensity of the sector. In smelting and refining, the increase in production level in the aluminum industry is the primary driver of increased GHG emissions, and in the iron and steel industry, industrial restructuring and increasing the share of electric arc furnaces (compared to basic oxygen furnaces) for steel production are the main drivers of change in GHG emissions.

2.4. Implications for policy

In order to develop effective GHG mitigation policies in the industrial sector, it is critical for policy makers and industrial stakeholders to understand the sector's main GHG emission drivers. This is important because Canada's industrial sector has a considerable share of emissions and increasing GHG emissions trends. The key observations from decomposition analysis, drivers of change in industrial GHG emissions, and the scale of the impacts on overall GHG emissions are summarized in Table 2-5.

Table 2-5: Key observation from the historical trends of individual factors (between 1990 and 2014)

Factor	Key observations	Drivers of change	Impacts on overall industrial emissions
Activity level	48% increase in industrial activity level	• The mining and construction industries were the main drivers of the jump in activity level with increases of 67% and 58%, respectively, from the 1990 level. • Increase in activity levels of all industrial sub-sectors except pulp and paper (-15%) and forestry (-7%).	• Activity level is the biggest contributor to the increase in industrial GHG emissions. • The mining and construction industries play the biggest role in the overall impacts of this factor. • The overall impact on industrial GHG emissions was +57 Mt CO_2eq between 1990 and 2014.
Industry structure	Other manufacturing, mining, and construction industries are the main contributors to the industrial sector's overall output.	• The share of these sub-sectors increased from 89% in 1990 to 92% of overall industrial output in 2014. • Shares of the construction and mining industries increased by 3% and 2%, respectively, and the share of other manufacturing decreased by 2.4%[3].	• The factors has been continuous and increasingly effective in GHG mitigation over time. • The overall impact on industrial GHG emissions was -24 Mt CO_2eq between 1990 and 2014.
Energy intensity	The overall energy intensity of the industrial sector decreased by 11% (from 9.3 MJ/$2007 GDP in 1990 to 8.3 MJ/$2007 GDP)	• Of the 10 industrial sub-sectors, the energy intensity of 7 has improved. • In construction, smelting and refining, and other manufacturing, the energy intensity improved by almost 33%. • The energy intensity of the forestry and mining sectors increased by 185% and 131%, respectively.	• The impact of this factor on industrial GHG emissions was be +23 Mt CO_2eq between 1990 and 2014. • The rate of energy efficiency improvement is slower than economic growth in Canadian industries.
Fuel mix	A shift toward the use of less carbon-intensive fuels was observed between 1990 and 2014.	• The consumption of heavy fuel oil, coke, and coal products decreased by 80%, 12%, and 21%, respectively. • In 2014, more than 86% of final energy consumption in the industrial sector was in the form of relatively low-carbon fuels (natural gas, electricity, still gas and wood wastes).	• The overall impact of the fuel mix on industrial GHG emissions was -7 Mt CO_2eq between 1990 and 2014. • The move toward low-carbon fuels has helped reduce overall GHG emissions from the industrial sector over time.
Emission factor	The emission intensity of Canada's electricity grid decreased by 24% in the time period of the study.	• The share of natural gas in the overall electricity generation mix increased from 2% in 1990 to 9% in 2014. • In the same time period, the share of heavy fuel oil decreased from 2% to almost 0% and the share of coal decreased from 16% to 10%.	• The overall impact of the EF on industrial GHG emissions was -10 Mt CO_2eq between 1990 and 2014, which makes the EF the biggest contributor to GHG mitigation from the industrial sector. • Carbon-intense electricity generation is the main factor affecting the emissions factor component.

[3] While changes in the overall shares of the mentioned industries range between -2.4% to +3%, the industries' overall activity level changed considerably (for example, from 1990 to 2014, the mining industries' activity level increased from 83,399 million CAD in 1990 to 132,193 million CAD). The combination of activity level of these industry and the large share that they have in the overall industrial output have resulted in the observed impact of industry structure on the overall industrial emissions.

2.4.1. Industrial activity and structure

Canada is a resource-rich nation, and industrial activities play a crucial role in the country's economic prosperity. Therefore, the increasing trends of industrial activities are expected to continue in the coming decades [200]. Economic diversification and increasing the shares of less carbon-intensive industries such as construction and forestry are expected to help reduce industrial GHG emissions in the long term. While the move toward less-carbon intensive industries has started in different Canadian provinces, more aggressive programs such as Alberta's economic diversification program, which was established recently and supports clean energy industries (among others) [201] and CleanBC which aims at reducing GHG emissions from different economic sectors including industrial sector [202], could be adopted by other provincial governments and the federal government to accelerate the transition toward low-carbon economy.

2.4.2. Energy efficiency

Analysis of the historical trends shows that industrial energy efficiency improvement has not helped mitigate GHG impacts in Canada. Currently there are 175 industrial energy efficiency programs at regional, provincial, and federal levels [203]. Yet there are no binding regulations for energy efficiency improvement. In other words, although industrial energy efficiency improvement is suggested as one of three action plans for GHG emissions reduction in the industrial sector in the Pan Canadian Framework on Clean Growth and Climate Change (PCFCGCC) [101], there are no binding targets or industry-specific requirements for energy efficiency improvement, and this needs to be addressed in the emerging regulations. The development of industry-specific energy and emissions benchmarks and standards could be the first step in quantifying energy efficiency targets in Canada's industrial sector.

In addition, historically, industrial energy efficiency improvement has not been among the government's top priorities for energy-related funding allocation [204]. Moreover, as a member of Mission Innovation, Canada committed to doubling its 2014-15 funding for clean energy and clean technology development to $775 million by 2020 [203], but energy efficiency is not among the challenges addressed by Mission Innovation [205]. While from the technology perspective energy efficiency measures are mature and often regarded as the most economically feasible measures for energy saving and GHG mitigation in industrial sector [19], from the practical point of view, financial incentives from governments and public agencies are crucial in accelerating energy efficiency in a sector as capital-intensive and resistant to change as the industrial sector.

2.4.3. Emission factor and electricity decarbonization

From the data, we found that Canada's industrial and electricity generation sectors are on the right path in terms of supporting fuel switching and decarbonizing electricity and should continue to support these initiatives. More specifically, the emissions factors from Canada's electricity generation are much lower than in other OECD countries [206, 207] and are expected to fall further because of recent regulations such as coal phase-out plans in Alberta, where most oil sands industries (the biggest contributor to national GHG emissions) are located [208]. Phasing out coal will escalate the impacts of fuel switching, i.e., increase the share of electricity in the industrial fuel mix. Therefore, maintaining the existing decarbonization regulations in Alberta, Ontario, and BC and adopting similar policy measures (e.g., coal phase-out in the electricity sector) in other industrial provinces such as Saskatchewan and Manitoba are expected to be the way forward for policy makers. However, as such regulations already exist in most electricity-consuming provinces, the trends of electricity decarbonization are expected to slow down in the coming decades.

2.5. Conclusion

In this study, the logarithmic mean Divisia index (LMDI) was applied as the decomposition method to disaggregate the Canadian industrial sector's GHG emissions to their driving forces. The study covers the full spectrum of the sector (both manufacturing and non-manufacturing). Activity level, industry structure, fuel mix, energy intensity, and GHG emission factors were considered as the main drivers of GHG emissions. In terms of the scope, 46 industrial sub-sectors were considered in the analysis. Furthermore, unlike earlier studies, this study analyzed the historical changes in each factor between and 1990 and 2014 and investigated how changes in factors affected industrial GHG emissions.

The results of decomposition analysis suggest that the biggest contributor to the increase in industrial emissions over the time period of the study is activity level. Changes in industry structure by promoting less carbon-intensive industries, increasing the share of low-carbon fuels, and improving the emissions factors of electricity generation helped reduce GHG emissions from the industrial sector both directly and indirectly. Despite the improvement in the energy intensity of several industrial sub-sectors, the overall energy intensity of the sector has worsened.

From a policy-making perspective, the study highlights that to realize the ultimate energy efficiency potential in Canada's industrial sector, binding energy efficiency standards and regulations are needed. While industry-specific standards and benchmarks are required to develop effective energy efficiency regulations, financial incentives will help accelerate the adoption of energy efficiency measures in the industrial sector.

Chapter 3 : Long-term energy efficiency improvement and greenhouse gas emissions mitigation in the cement industry: A case study for Canada[4]

3.1. Introduction

Historically, the cement sector has been responsible for between 5% and 9% of global greenhouse gas (GHG) emissions [209-211]. In 2010, more than 2,800 million tonnes of GHGs were emitted from the industry, a figure corresponding to 9% of global CO_2 emissions [211]. In addition, the fast growth rate of the industry (more than 200% increase between 2003 and 2015) [212] highlights the increasing role of the cement industry in global CO_2 emissions; and emphasizes the importance of GHG mitigation in this sector.

In the cement industry, CO_2 is generated not only through fuel combustion but also as an inherent part of the process (i.e., calcination) [209]. Direct fuel-related emissions result from fuel combustion on the production site, and indirect emissions are generated as a result of electricity consumption. Depending on the source of emissions, there are various GHG mitigation strategies, i.e., process modification, energy efficiency improvement, and the use of alternative materials [213].

The applicability of the GHG mitigation options in the cement industry is subject to several factors including technological and economic performance and the effectiveness of the options in reducing GHG emissions. For example, for assessing the energy savings and GHG mitigation

[4] A version of this chapter was published as Talaei A, Pier D, Iyer AV, Ahiduzzaman M, Kumar A. "Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation options for the cement industry." Energy, 2019; 170: 1051-1066.

potential in the cement industry, detailed technology assessment has been proved to be an effective tool [209]. Scenario analyses are also used in some studies to investigate the performance of the cement industry on regional and national levels [214, 215]. While these studies mainly focus on the long-term applicability of different options and analyze the achievable mitigation potential through implementing the options, other studies assess the economic performance of the energy efficiency technologies through various economic indicators. In a European-wide study, for instance, different techniques such as payback period, net present value, and internal rate of return were used to analyze the economic feasibility of energy efficiency improvement in the cement industry [216]. Similar studies have been done in China and the United States [217, 218], where economic factors together with the performance indicator of different technologies (i.e., energy savings potential) are used to analyze the cost of saved energy and develop conservation supply curves. Madlool et al. [25] reviewed the global status of the cement industry in terms of energy use and energy saving potential. They also analyzed various energy saving options, their GHG mitigation potential (calculated based on the reduction in energy consumption), and the payback period (calculated for some of the options where calculations were based on the energy saving alone) [219].

Analyzing the existing literature reveals that despite the important role that cement industry could play in the global GHG mitigation, the long-term system-level evolution of the sector and the role that energy efficiency improvement could play in mitigating GHG emissions from the sector is less understood. In other words, comprehensive literature review reveals that the most common methods for analyzing the industrial energy efficiency improvement are techno-economic assessment [216-226] and policy analysis [227-231]. While the former set of studies focus mainly of the specific energy efficiency process or technology, the latter applies a high level perspective to assess the energy efficiency improvement potential at system level (with less emphasize on the technological performance of individual processes).

Application of bottom-up energy modelling and scenario analysis could help bridging the gap between technology-specific energy efficiency analysis and system-wide GHG mitigation assessment (while considering the development of the energy system at different levels). Although the bottom-up energy modelling techniques has been widely used to study the long-term development of the sectors such as electricity generation, residential, transportation etc., [32, 50-58, 82, 102, 232, 233], complexity of the industrial sector and the role of energy carriers both as a source of energy and in some industries as a feedstock has imposed limitations on application of the method in industrial sector energy efficiency analysis.

Therefore, the primary objective of the current study is to develop a detailed and technology-rich bottom-up energy modeling framework (including both energy supply and demand sides) to assess the technologically feasible GHG mitiation potential while accounting for the intractions between the energy supply and demand sectors. This helps, analyzing the actual emissions mitigation potential (a combination of direct mitigation at the demand point and indirect mitigation as a result of electricity conumption). In addition, different economic indicators (namely cost of saved energy and GHG mitigation cost) are calculated to assess the economic performanc of different GHG mitigation efforts.

In summary, the proposed framework is applicable for analyzing the current status of the system by identifing the major energy consumers (at process and technology level) and assessing the applicable energy efficiency measures and their adoption potential. This provides the ground to develop long term mitigation scenario to evaluate the GHG mitigation potential and its associated cost.

The detailed and technology-rich framework is flexible and could be easily transferred in the scientific community to study the long-term GHG mitigation potential of the cement industry in different jurisdictions. In addition, given the considerable share of the energy in the overall cost of industry, share of cement industry in the global GHG emissions and the existing and emerging regulations around carbon emissions at both national and global levels, the results of the analysis are expected to provide invaluable input to both industrial stakeholders and policy makers.

3.2. Methods and material

3.2.1. The Canadian cement industry

The cement industry accounts for about 1.6% of energy consumption and about 2.4% of the GHG emissions in Canada´s industrial sectors [234]. The overall emission intensity (i.e., kg CO_2/tonne cement) of the industry decreased by slightly less than 10% over between 2002 and 2010 (see Figure 3-1). This decrease is due to both energy intensity improvement and process modification.

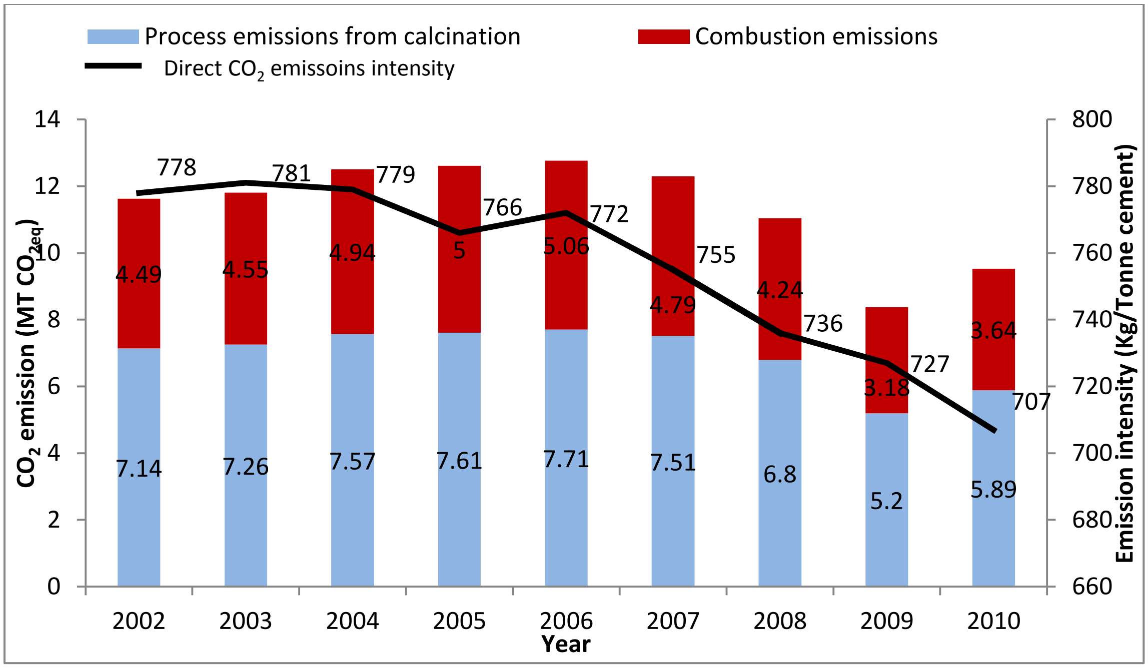

Figure 3-1: Historical GHG emissions from the Canadian cement industry (derived from [197])

In terms of process energy intensity improvement, over the past decade, the industry has shown continuous improvement, i.e., the overall energy intensity of the cement production process decreased from 3.909 GJ/tonne cement in 2002 to 3.481 GJ/tonne cement in 2010. This was achieved mainly through improvements in thermal energy efficiency. The electrical energy intensity of the process has remained almost constant [197].

In terms of process modification, the clinker-to-cement ratio decreased from 87% to 80% between 2002 and 2010. Substituting clinker with alternative materials such as fly ash, kiln dust, and steel slag has reduced the demand for kiln-fired materials. Although the clinker-to-cement ratio has improved considerably in the past few years, compared to the global best practices, Canada is still lagging behind and industry performance is lower than the global average [197].

3.2.2. The LEAP model

The Long-range Energy Alternative Planning system (LEAP model) is long-term GHG mitigation scenario analysis and policy development framework [32, 35]. The model is an integrated planning tool that can be used to track the energy flow through all economic sectors including energy consumption, production, and extraction (Figure 3-2). LEAP model is one of the few energy modelling tools with the features to conduct both top-down and bottom-up energy modeling [32, 33]. In other words, LEAP is a hybrid model which combines the features of various energy system accounting, evolution and simulation models [35].

Energy modelling in LEAP provides the opportunity to account for the interaction between different modules within the energy system. More specifically, simultaneous consideration of energy supply, transformation, distribution, and demand sectors helps the energy modeler to account for sectoral development and the progress in the energy system at different levels.

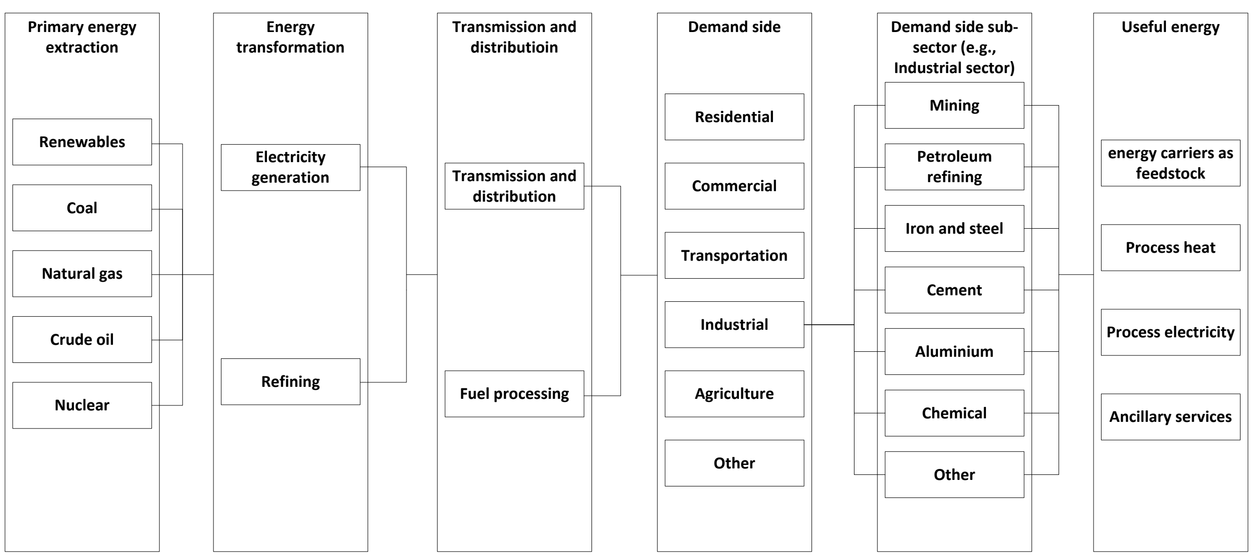

Figure 3-2: Simplified structure of energy system in the LEAP model

While the detailed description of the developed energy supply model is provided by the earlier studies of the authors [66], detailed description of the model development for cement industry is provided in sections 3.2.3 to 0.

3.2.3. Overall methodology for model development

Energy modelling and scenario analysis are proven methods for energy system analysis and energy forecasting [81, 82, 235-238]. In this study, long-term scenario analysis was used to evaluate the GHG mitigation potential in the cement industry. Following an analysis of the current status of the cement industry a baseline scenario was developed in order to forecast the cement sector development and associated energy consumption. In addition, several mitigation scenarios were developed to assess the achievable GHG reduction potential in the sector. In order to assess the incremental costs of implementing energy efficiency measures (i.e., mitigation scenarios), a cost benefit analysis was conducted. Then the incremental costs and the GHG reduction potential were used to develop emissions mitigation cost curves, which help understand the cost to mitigate one tonne of carbon by a particular technology over a particular period of time. Figure 3-3 shows the overview of the methodology used in this study.

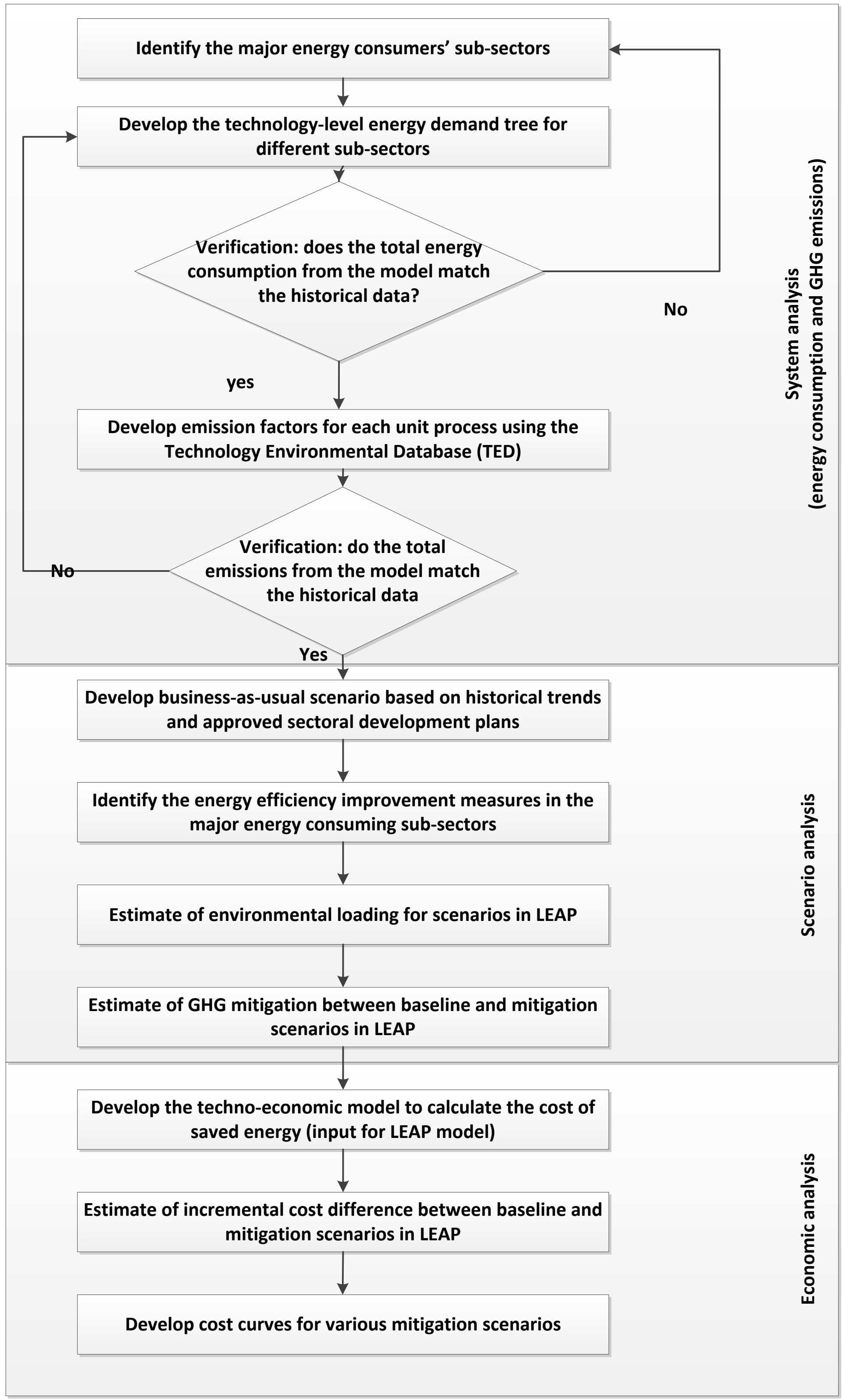

Figure 3-3: Overview of the methodology for developing GHG mitigation cost curve

As shown in Figure 3-3, modelling has different stages including analyzing the historical and current status of the industry (i.e., energy consumption demand tree development and data validation), developing scenarios (baseline and GHG mitigation), and performing cost benefit analyses. The details of each step (i.e., assumptions and model development) are described below.

3.2.4. System analysis and base year model development

The system analysis includes investigating the cement production process, identifying the major energy-consuming sub-processes, and developing the energy consumption demand tree. In other words, in order to develop an energy consumption demand tree, the energy intensity[5] of the major energy-consuming sub-sectors needs to be analyzed.

3.2.4.1. Process analysis

The Portland cement manufacturing process involves almost 80 separate and continuous precise operations, the use of heavy machinery and equipment, and large amounts of heat and energy. In general, the Portland cement production process is identical for gray and white cement. However, depending on the type of cement, the proportions of raw materials vary. For example, in gray cement production, limestone, silica, alumina, iron are the main feedstock, while for white cement, almost no iron is required. For both gray and white cement, there are three main stages in the production process: kiln feed preparation, clinker production, and grinding, finishing, and distribution.

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[5] In this Chapter, energy intensity is defined as the amount of energy consumed per unit of final product (i.e., GJ/Tonne cement)

- Kiln Feed Preparation

Raw material for cement production comes from quarried materials like limestone and chalk as well as clay from mines. Limestone supplies the $CaCO_3$ and is the primary raw material, and silica, alumina, $MgCO_3$, and iron are also used [26]. Raw material processing is an electricity-intensive process. The moisture content of raw material (i.e., products of the kiln feed preparation process) vary depending on the clinker production process [217]. More precisely, the moisture content of the materials is between 0 and 0.7% for the dry process and between 24% and 28% for the wet process [217]. While further drying of the feedstock (for the dry process) results in more electricity consumption, the process needs much less thermal energy in the subsequent stages (i.e., clinker production)[6] [26].

- Clinker Production

Clinker production is the biggest energy-consumer sub-sector in the cement production process and accounts for almost 90% of the energy use in production processes [217]. Clinker is produced in large kilns through pyro-processing. These kilns heat the mixture, evaporate the free water, calcine the carbonate constituents in a process called calcination, and form Portland cement material (i.e., clinkerization). In the clinkering process, the temperature reaches about 1800- 2000° Celsius (in the sintering zone) [217]. In order to ensure cement hardness, the products need to be cooled down rapidly; this is usually done in a grate or planetary cooler [217]. There is usually a pre-calciner/preheater included in the clinker process, which improves energy efficiency (per tonne of clinker production) by more than 36% [26].

- Grinding, Finishing, and Distribution

[6] Various degrees of wet processing exist (e.g., semi-wet [moisture content of 17-22%]), to reduce the fuel consumption of the kiln.

In this stage, clinker is transported to the finishing process using different types of conveyors. In order to control the properties of cement, 5% gypsum is added during clinker production [217]. The main energy carrier used in the finishing and grinding process is electricity, the amount of which varies depending the properties of the final product but does not exceed 5% of the total energy consumption of cement production [217]. The typical cement production process is shown in Figure 3-4 (adapted from [217, 239]).

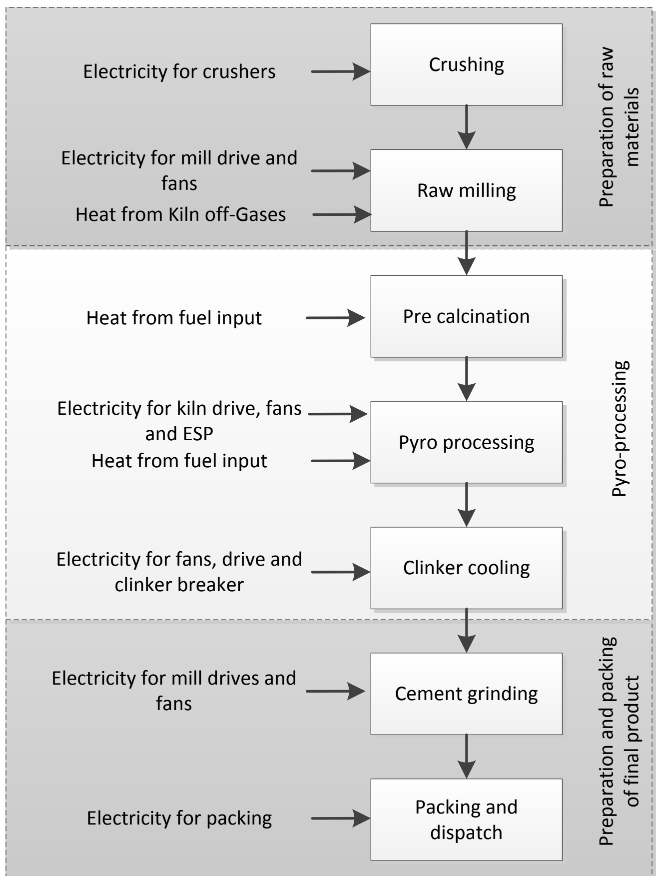

Figure 3-4: Cement production process [217, 239]

3.2.4.2. Energy intensity analysis

In order to evaluate the energy intensity of different sub-sectors, a comprehensive literature review was done, and the process-level data was validated against aggregated industry-level data reported by Natural Resources Canada (NRCan) [234]. As shown in Table 3-1, the energy intensity of the cement industry in the United States improved from 4.45 GJ/t in 1999 to 3.65 GJ/t in 2009 [240-242]. This is in line with the data from the Canada Centre of Mineral and Energy Technology, where the energy intensity of cement production was forecast to reach 3.85 GJ/tonne by 2010 [243], and the data reported by the Cement Association of Canada that gives the energy intensity data for 2002 and 2010 to be 3.909 GJ/tonne cement and 3.481 GJ/tonne cement, respectively [197]. In other words, similarities in the Canadian and American cement industries justify considering the data interchangeably [114].

Table 3-1: Energy intensity of cement production (Portland cement) (derived from [240-242])

	World Best Practices		US Cement Industry (1999)		US Cement Industry (2009)	
	Heat	Electricity	Heat	Electricity	Heat	Electricity
	(GJ LHV/tonne cement)					
Kiln Feed Preparation	-	0.07	-	0.24	-	0.20
Clinker Production	2.71	0.08	3.85	0.156	3.12	0.11
Finish Grinding	-	0.07	-	0.206	-	0.21
Total	**2.93**		**4.45**		**3.65**	

As shown in Table 3-1, the energy intensity of average North American cement industries is higher than world best practices. This is mainly because of the long lifetime of the industrial infrastructure and its slow turnover rate. In other words, while more energy-efficient technologies are available on a commercial scale globally, their adoption rate by industry is relatively slow and therefore the average energy intensity of existing technologies is higher than the state-of-the-art technologies. Despite improvements in sector energy intensity between 1999 and 2009, there is still potential for efficiency improvement (i.e., comparing existing technologies with the world best practices).

As shown in Figure 3-5, different types of energy are used in the Canadian cement industry. While overall energy consumption of the industry shows decreasing trends, the shares of different fuels are changing over time. More precisely, in the past decade, the shares of electricity and petroleum coke have been almost constant whereas natural gas has been steadily replacing coal [244]. It is important to consider the fuel share of the overall energy consumption in the industry as combustion of heavier fuels such as coal and petroleum coke would result in higher emissions compared to the lighter hydrocarbon fuels such as natural gas. In other words, Figure 3-5 shows that in the past decade the share of natural gas in the fuel mix of cement industry has increase (while the share of coal has decreased) which has helped improving the carbon intensity of the industry (Figure 3-1).

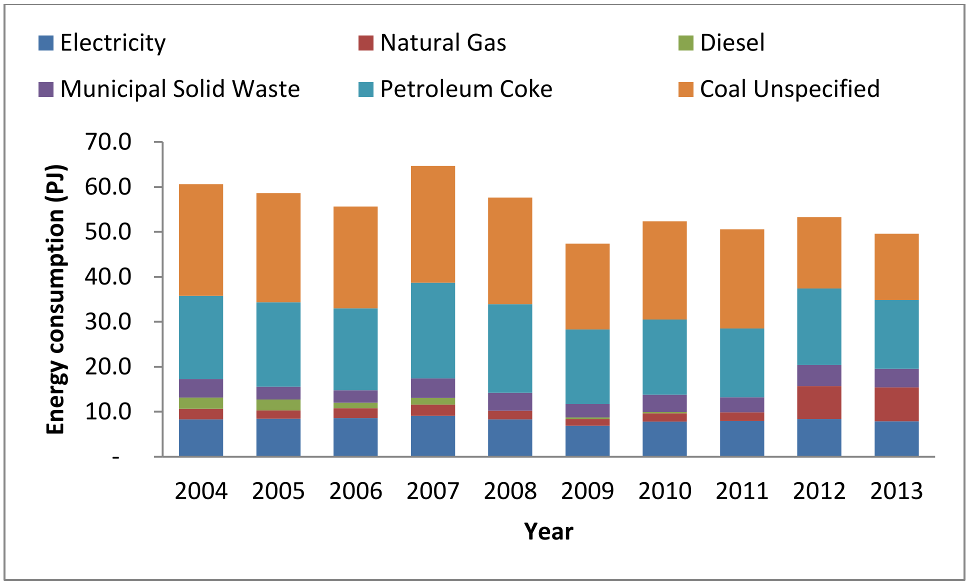

Figure 3-5: Fuel shares for the clinker production process in Canada [244]

3.2.4.3. Energy consumption demand tree

The energy intensity data (Table 3-1) and the share of different fuel types consumed in each process (Figure 3-5) are used to develop the energy consumption demand tree (Figure 3-6). The intergovernmental Panel on Climate Change's Tier one default emission factors are used to calculate the direct emissions at the point of consumption [245]. Where applicable, these data were updated to represent the case of Canada. The indirect emissions from electricity consumption were derived from the supply side model and represent the structure of the current and future structure of the electricity sector in Canada.

While the 2009 data are shown here to illustrate the analysis, the gradual changes in intensity between 1999 and 2009 are accounted for during the system analysis and model verification.

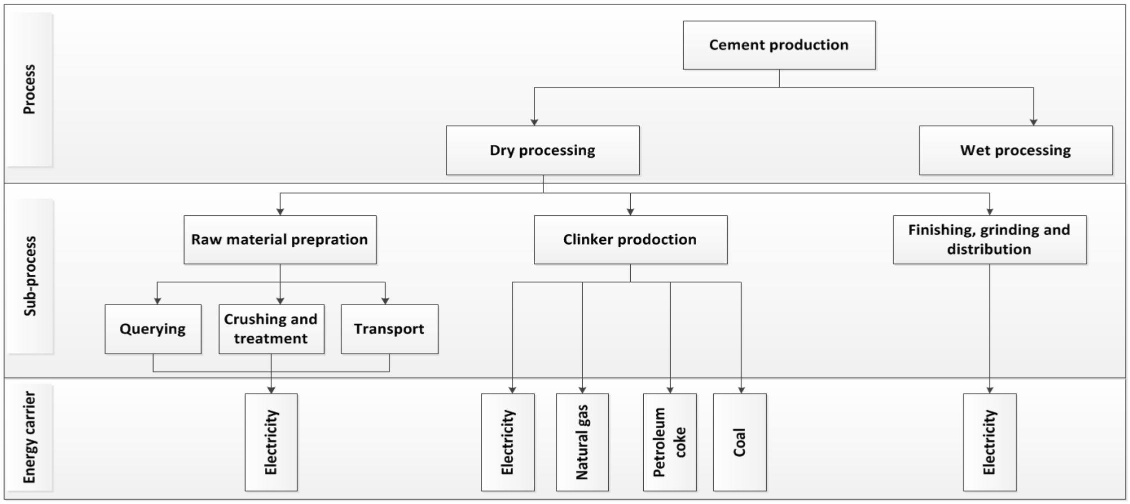

Figure 3-6: Energy consumption demand tree

3.2.5. Model verification

The assumptions about the energy intensity of different sub-processes are validated by comparing the LEAP model results on aggregated energy consumption and GHG emission data at the industry level with those reported by Natural Resources Canada (NRCan)'s actual energy consumption. The verification results for industry-wide energy consumption and GHG emissions are shown in Figure 3-7 and Figure 3-8 respectively.

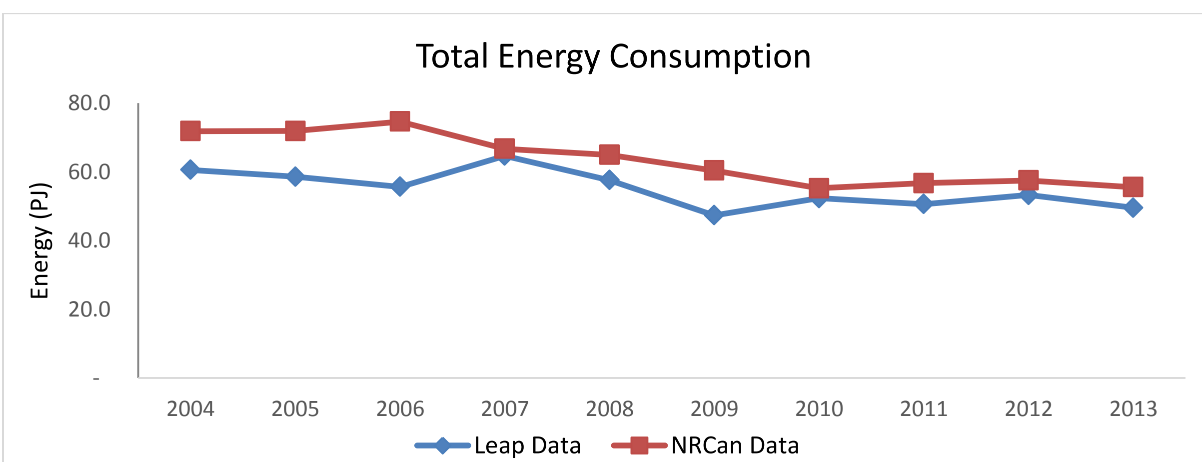

Figure 3-7: Total energy consumption by the cement industry in Canada

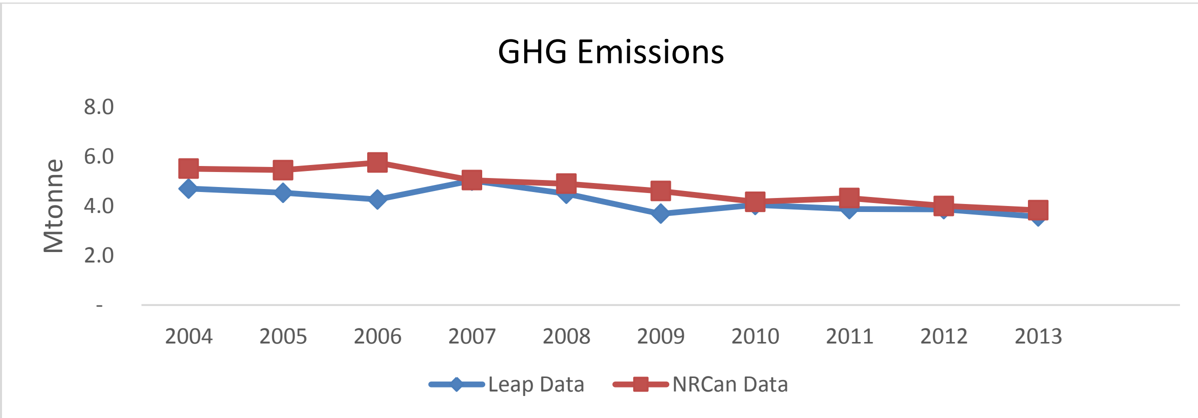

Figure 3-8: GHG emissions from the Canadian cement industry

As shown in Figure 3-7 and Figure 3-8, the results of the LEAP model are in line with aggregated industry data reported by NRCan [234]. Data validation is done not only for aggregated fuel consumption but also for different energy carriers. Details of the analysis for different fuel types are provided in Appendix II-I.

3.2.6. Scenario analysis

In order to assess the future energy saving and GHG mitigation potential, a baseline scenario (also referred to as the reference or business-as-usual scenario [BAU]) and several GHG mitigation scenarios were developed. The year 2010 is considered the base year. This ensures the availability and consistency of different data used in the analysis[7] (i.e., cement production, energy consumption, and GHG emission data).

Two time horizons (ending in 2030 and in 2050) are used to develop fast and slow penetration scenarios. For each scenario, it is assumed that the full implementation of the energy saving

[7]Where applicable, more recent data are used, for example for systems-level data analysis and validation.

measures would be realized by the end of the study period. In other words, in the fast penetration scenario (i.e., 2030 time horizon), it is considered that the full potential for energy efficient technology diffusion would be realized by the end of 2030. In the slow penetration scenario (i.e., 2050 time horizon), it is considered that energy efficient technology penetration would occur gradually and full implementation potential would be realized by the end of 2050.

In terms of system development, the national demand for cement and concrete products together with the average historical demand-to-export ratio of 63% is considered for predicting future industry development [246]. The North American cement production forecast [246] together with the historical share of import and export and the clinker production share are used to forecast cement production in Canada to 2050. Based on these, an annual growth rate of 0.71% is considered for industry development from 2017-2050.

3.2.6.1. Baseline scenario

The reference scenario was developed to predict future cement sector development and to forecast associated energy consumption and GHG emissions if no action for emission mitigation takes place. As the basis for comparison, it is assumed that sector development would follow the historical trend, and sectoral development plans (as announced by the provincial and federal governments and the private sector) will take place as planned. In terms of energy efficiency improvement, it is assumed that there will be no major changes in the energy intensity of different cement production sub-sectors.

3.2.6.2. Alternative scenarios

Energy efficiency improvement scenarios were developed to assess the long-term effectiveness of each technology option in reducing the energy consumption and mitigating the GHG emissions from the cement industry. There are two steps in developing the alternative scenarios: I) identifying the energy saving options and II) assessing the technological performance of the technologies.

- Identification of energy efficiency options

The energy efficiency and environmental performance of the Canadian cement industry has improved steadily in the past decade. From 2002 to 2010, cement plant modernization has led to a 17% improvement in overall energy efficiency of the process [197]. However, as shown in

Table 3-2, there is potential for further energy efficiency improvement (when comparing the North American industry with world best practices) by implementing energy efficiency measures or even by applying emerging technologies/processes with lower energy and environmental footprints. In other words, in addition to energy efficiency measures that could help the industry reach the world's best practice standards, the intensity could be further improved if fundamental changes in the process occur. For example, using fly ash and blast furnace slag (by-products of iron and steel industry) can reduce the energy intensity to 2.11 GJ/t and 1.75 GJ/t, respectively, (as shown in

Table 3-2) compared to the existing intensity of 3.65 GJ/t.

Table 3-2: World best practices for fly ash- and blast furnace slag cement (GJ/tonne cement) [247]

	Fly ash cement		Blast furnace slag cement	
	Heat	**Electricity**	**Heat**	**Electricity**
Kiln feed preparation		0.05		0.03
Clinker production	1.9	0.05	1.0	0.03
Finish grinding		0.08		0.15
Additives preparation		0.03	0.45	0.09
Total in GJ/t	2.11		1.75	

A comprehensive literature review was conducted to identify the globally available energy efficiency measures for the cement industry [217, 241-243, 248-263]. Increasing the share of semi-dry and dry processes [26], waste heat recovery [264-267], and energy recovery from different processes [27, 268, 269] helps improve energy efficiency in the industry. With the considerable potential for CO_2 capture, carbon capture and storage (CCS) is a mitigating technology that is expected to be introduced in the industry in mid to long term [270]. Application of alternative materials is also found to be an effective measure for reducing carbon emissions from the industry. The alternative materials considered in scientific studies are classified as alternative fuels or alternative raw materials to replace clinker; they are expected to reduce the emissions related to fuel consumption and the clinker production process, respectively. Examples of alternative fuels are animal waste [271], wood waste [272], and sewage sludge [273]. Alternative fuels could replace the commonly used fossil fuels in the cement industry and therefore potentially reduce CO_2 emissions [213]. Industry by-products could be used as substitutes for clinker. Examples include fly ash [274] and blast furnace slag (a by-product of the steel industry) [275], which could replace some of the clinker in the cement process (i.e., decrease the clinker factor) and therefore help reduce the overall emissions from the industry.

A list of the 41 identified energy efficiency/emissions mitigation measures in the cement industry is provided in Appendix II-II. In general, the different measures for reducing CO_2 emissions from the cement industry could be classified in three main categories as shown in Figure 3-9.

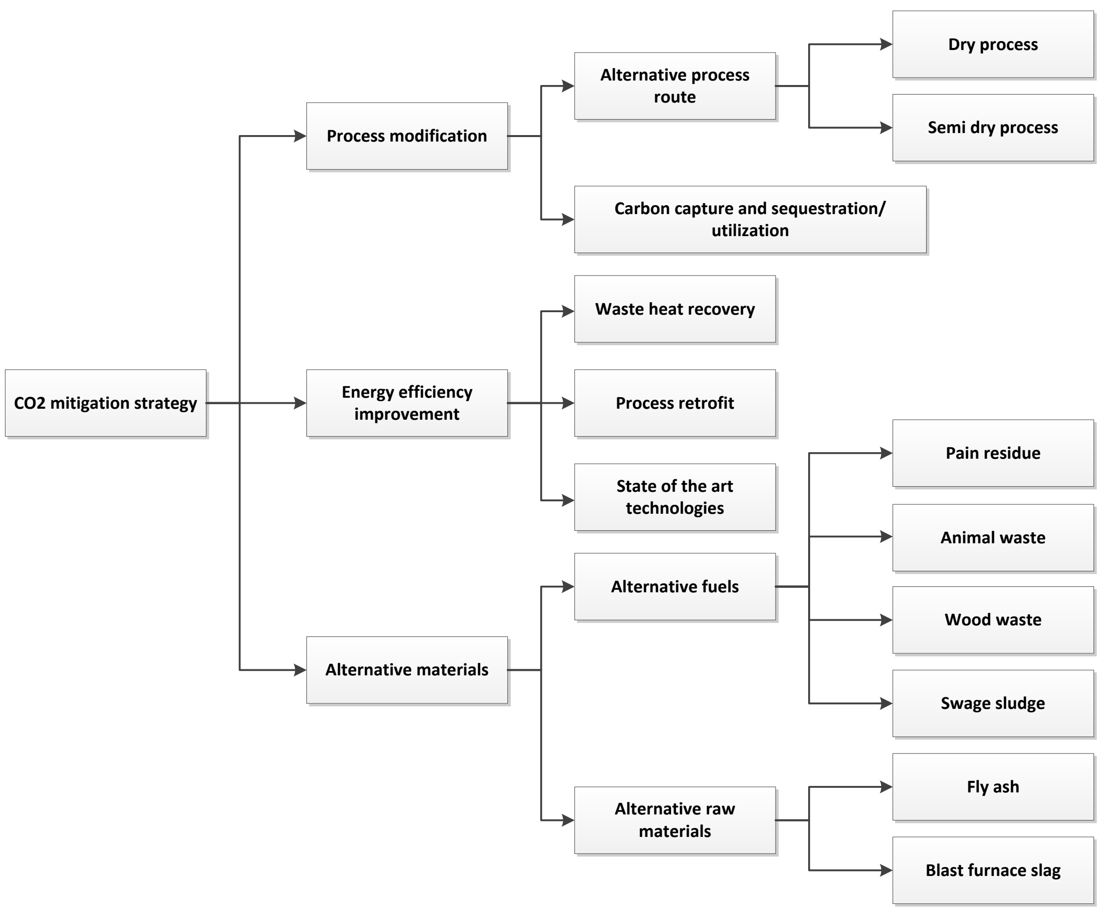

Figure 3-9: CO2 mitigation strategies in the cement industry

The applicability of the identified options was assessed for the Canadian industry and selected a final set of 10 technologies for scenario analysis. The applicability of energy efficiency measures was assessed based on several assumptions:

- The identified energy efficiency options for the wet kiln processing were excluded from the analysis (i.e., they had an applicability rate of zero) as the last two wet kiln processing plants (located in Woodstock) were closed in 2008 and currently only dry processes exist in Canada.
- Only state-of-the-art technologies were considered. More precisely, observing the considerable energy intensity improvement between 2000 and 2013, technologies such as ball mill load level control system, high efficiency separators, etc. as identified by Holderbank [243] were excluded from the current study. The options identified in that study were expected to be implemented in the Canadian cement industry by 2000 and it is reasonable to assume that the industry adopted those technologies 17 years later (by 2017).
- The identified options were classified based on their operations and purpose of implementation. For example, all the preheating technologies were classified in one category, from which only low pressure drop cyclones were considered for the analysis. In other words, it is considered that the implementation of low pressure drop cyclones would eliminate the need for other types of preheaters. Similarly, among all the heat recovery options in the clinker production process, only one technology was chosen where the criterion for selection was energy saving and GHG mitigation potential.

A list of the selected energy efficiency measures is provided in Table 3-3.

Table 3-3: Energy efficiency options for Canadian cement industry

Efficiency measure	Description
Adjustable speed drive for kiln fan	Adjustable or variable speed drives (ASDs) for the kiln fan reduce maintenance costs and power consumption. Depending on the configuration of the plant, they can save up to 40% of electricity consumption.[252] Lafarge Canada´s Woodstock replaced their kiln fans with ASDs and reduced electricity use by 5 kWh/t [253].
Blended cement	For the production of blended cement, additives (i.e., granulated blast furnace slag, fly ash, silica fume, or volcanic ash) are interground in the clinker. Intergrinding the additives reduces energy consumption and carbon emissions and will offset the environmental impact. Energy savings are estimated at 0.4-1.6 MBTU/ton cement [256].
Conversion to reciprocating grate cooler	Modern reciprocating grate coolers (3rd generation) increase the productivity of the kiln and have a higher heat recuperation efficiency (70-75%). By upgrading a planetary or rotary cooler, fuel savings up to 8% are possible. Upgrading modern coolers is economically attractive when production needs to be expanded or a precalciner is installed [254, 256].
Energy management and process control systems	Optimization of the combustion process and conditions using expert systems, model-predictive control (MPC), or fuzzy logic systems can lead to energy savings between 2.5 – 10 %, 0.04-0.17 MBTU/ton, respectively [256]. A process control of the clinker cooler can reduce energy consumption by 5%, increase cooler throughput by 10%, reduce free lime by 30%, and reduce NOx emissions by 20% [276].
Fuel switching	Switching the fuel can increase clinker fuel consumption by 0.26 MBTU/ton or decrease it 0.17 MBTU/ton, depending on the switch [256]. Because combustion accounts for one-third of the overall CO_2 emissions, switching fuels can reduce/increase CO_2 emissions.
Improved refractories for clinker making	Refractories protect the steel kiln shell against chemical, mechanical, and heat stress. New refractories have extended lifetimes and additional energy savings of about 54 kBTU/ton [277].
Indirect firing for clinker making	This technology is standard for modern plants. Because primary air supply is decoupled from the coal mill, lower percentages of primary air are used, which can save 43-63 kBTU/ton (by upgrading a mono- to multi-channel burner [256]. Upgrading from a direct to an indirect firing system can reduce energy by up to 162 kBTU/ton[277].
Kiln combustion system improvements	Improved combustion systems optimize the mixing of combustion air and fuel while reducing the use of excess air and also optimize the shape of the flame. Fuel savings of up to 10% can be achieved [278].
Optimized heat recovery upgraded clinker cooler	The clinker cooler reduces the clinker temperature from 1200 °C to 100 °C. Upgrading the clinker cooler can save 0.08 MBTU/ton [257].
Replacing vertical shifts with suspension preheater	Upgrading cyclones will reduce the power consumption of the kiln exhaust gas fan system. For older kilns, energy consumption when cyclones are replaced, can be reduced by 4kWh/ton [253].

As expected, the majority of the identified and selected energy efficiency options are in the clinker production process. This is because kiln production accounts for 90% of the total energy consumption of the cement production process, or almost 33% and 99% of the overall electricity and fuel consumption, respectively.

- Technological performance

Each of the technology options identified in 0 are assessed in terms of their fuel and electricity saving potential, their associated costs, and their applicability in the Canadian cement industry (

Table 3-4). According to the Canadian Cement Industry Energy Benchmarking study, only 4 of the 15 existing cement plants in Canada are performing better than the technical best practices (TBP) where finish grinding is the best performing sub-sector and feedstock preparation sub-process (Figure 3-10) [279]. This, together with the real-world adoption data provided by the Industrial Efficiency Technology Database (IETD) [280], is used to estimate the applicability and adoption rate of the identified technologies.

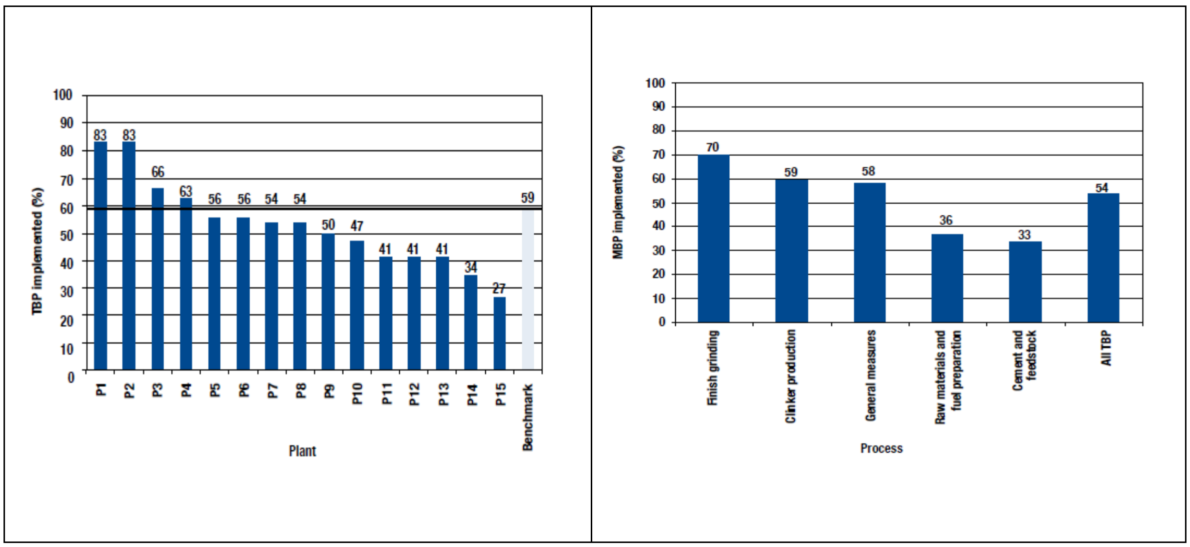

Figure 3-10: Penetration of applicable technical practices by plant and process [279]

Table 3-4 Energy efficiency options for the cement industry [217, 241-243, 248, 250, 252-257]

NO.	Energy Efficiency Options	Fuel Saving (GJ/t)	Electricity Saving (kWh/t)	Selected Values		Capital Cost (CAD /tonne)		App. (%)
				FS (GJ/t)	ES (kWh/t)	Literature	Selected	
1	Adjustable speed drive for kiln fan	0.05 - 0.068	4.95 - 6.1	0.06	5	0.23	0.23	50
2	Blended cement	0.46 - 1.86	NA	0.5	0	7-14	10.5	50
3	Conversion to reciprocating grate cooler	0.22	NA	0.22	0	0.5 - 12.6	10	60
4	Energy management and process control systems	0.1 - 0.2	0- 4.2	0.14	2.6	0.3 -1.7	0.9	90
5	Fuel switching	0.18 - 0.32	0 - 2.5	0.25	1.25	1.5 - 4.5	3	30
6	Improved refractories for clinker making	0.06 - 0.63	NA	0.35	0	0.17 - 0.6	0.6	30
7	Indirect firing for clinker making	0.015-0.18	NA	0.12	0	7.4 - 8.4	8	50
8	Kiln combustion system improvements	0.2	NA	0.2	0	0.98-1	1	20
9	Optimized heat recovery upgraded clinker cooler	0.05-0.1	NA	0.08	0	0.1 - 0.33	0.2	50
10	Replacing vertical shifts with suspension preheater	2.4	NA	2.4	0	28 - 41	35	80

3.2.7. Economic analysis

An economic analysis is done to calculate the cost of saved energy (CSE) and the GHG mitigation cost (CSC). We calculated the CSE using an external techno-economic model and the CSC in the LEAP model using the net present value (NPV) method.

3.2.7.1. Cost of saved energy

The cost of saved energy (CSE) is defined as the cost associated with mitigating one unit of energy consumption (i.e., CAD/GJ) and is used as an exogenous parameter in the LEAP model.

The CSE is an index for assessing the economic feasibility of an energy efficiency investment and is defined as shown in Equation 3-1 [281].

$$CSE = \frac{\sum(C_{EE} - C_{Base}) + \sum(O\&M_{EE} - O\&M_{Base}) + \sum(F_{EE} - F_{Base})}{\sum EC_{Base} - EC_{EE}} \qquad \text{Equation 3-1}$$

In Equation 3-1, different cost components including capital cost (C), operation and maintenance cost (O&M), and cost of fuel (F) are considered for both existing technologies (Base) and the energy efficient technology (EE). For the years 2015-2035, National Energy Board projections (reference scenario) are used for the price of fuel [282]; the data were simply extrapolated to forecast fuel price after 2035. All the costs are annualized, and the difference between the summation of the costs for energy efficiency and base technologies are used in the numerator of the equation. The denominator is the difference between the energy consumption of the energy efficiency and the base technologies. A cost value of 5% is used to account for the time value of the investment and expenses. In addition, technology lifetime and annual changes in fuel costs are considered in the analysis [282].

To calculate the CSE, we used the National Energy Board's fuel price projections [282]. In the techno-economic model, the fuel price projection is the weighted average among the Canadian provinces where cement is produced[8].

3.2.7.2. GHG mitigation cost

The CSC is defined as the cost associated with reducing one tonne of carbon dioxide emissions. The net present value is used as the economic indicator for calculating the GHG mitigation cost.

[8] It is considered that the share would not change during the time period of the study.

The NPV is an economic index that presents the value of investment using the future cash flow (revenues minus expenses) and the discount rate and is calculated as shown in Equation 3-2:

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i} \qquad \textbf{Equation 3-2}$$

In Equation 3-2, i is the year, n is the time period of the study, CF_i is the net cash flow in year i, and r is the discount rate. The NPV of different options is directly extracted from LEAP. The GHG mitigation cost is calculated using the cumulative GHG emission reduction and NPV of each option.

3.3. Results and discussion

A baseline scenario together with twenty mitigation scenarios was developed in the LEAP model. The baseline scenario was developed to serve as the basis for comparison and represent the system development following the business-as-usual trends. Ten energy efficiency/emissions mitigation scenarios were considered for alternative scenario analysis. The effectiveness of each of the energy efficiency options in reducing GHG emission was assessed in both fast and slow penetration scenarios. In the fast and slow penetration cases, it was assumed that the identified technologies would be fully implemented by the end of 2030 and 2050 respectively. In other words, while the overall uptake potential of these technologies was calculated and considered to be constant, two different technology penetration pathways (i.e., fast and slow penetration scenarios) were considered for each option and the impacts of penetration rate of the technologies on the overall achievable GHG mitigation potential from the industry was analyzed. Equation 3-1 was used assess the cost of saved energy for different options and develop a techno-economic model. The model results (i.e., the CSEs) as presented in Table 3-5 are used as input for the LEAP model.

Table 3-5: Cost of saved energy by scenario

Scenario No.	Energy-efficiency improvement scenarios	CSE (CAD/GJ)			
		2010-2020	2020-2030	2030-2040	2040-2050
Scenario 1:	Adjustable speed drive for kiln fan	-5.61	-6.17	-6.93	-8.02
Scenario 2:	Blended cement	-0.31	-0.5	-0.7	-0.93
Scenario 3:	Conversion to reciprocating grate cooler	6.15	5.97	5.76	5.53
Scenario 4:	Energy management and process control systems	-2.16	-2.55	-2.98	-3.56
Scenario 5:	Fuel switching	-0.68	-0.93	-1.2	-1.53
Scenario6:	Improved refractories for clinker making	-0.94	-1.12	-1.33	-1.56
Scenario 7:	Indirect firing for clinker making	4.27	4.09	3.89	3.65
Scenario 8:	Kiln combustion system improvement	-0.68	-0.86	-1.06	-1.3
Scenario9:	Optimize heat recovery/upgrade clinker cooler	-0.88	-1.06	-1.26	-1.5
Scenario 10:	Replacing vertical shifts with new suspension preheater	3	2.82	2.62	2.38

The CSE is used in the as input factor in the LEAP model. In the model, the simultaneous development of energy supply and demand was assumed. More precisely, the development of electricity generation and the distribution sector and its impact on associated emission factors with electricity consumption were taken into consideration. Cumulative energy saving and GHG mitigation potential for different mitigation options are given in Table 3-6 for both the fast and slow penetration scenarios. Energy savings and GHG mitigation data in Table 3-6 are cumulative and represent the cumulative saving compared to the baseline scenario during the time period of the study.

Table 3-6: Results of the LEAP model

Scenario No.	Energy-efficiency improvement scenarios	Fast penetration scenario (2010-2030)				Slow penetration scenario (2010-2050)			
		Cumulative energy reduction, PJ & GHG mitigation, Mt compared to reference scenario		Incremental NPV (million $) & GHG abatement cost $/tonne of CO_{2eq}.		Cumulative energy reduction, PJ & GHG mitigation, Mt compared to reference scenario		Incremental NPV in million $ and GHG abatement cost $/tonne of CO_{2eq}.	
		Energy	GHG	NPV (m)	$/ tonne	Energy	GHG	NPV (m)	$/ tonne
Scenario 1:	Adjustable speed drive for kiln fan	6.56	0.50	-267.59	-535.7	14.1	1.05	-360.3	-343.8
Scenario 2:	Blended cement	87.12	8.13	-23.22	-2.86	188.9	17.6	-37.2	-2.11
Scenario 3:	Conversion to reciprocating grate cooler	21.64	2.02	296.71	146.94	46.7	4.4	343.9	78.96
Scenario 4:	Energy management and process control systems	22.14	2.1.96	-201.06	-102.38	47.7	4.2	-280.3	-66.6
Scenario 5:	Fuel switching	26.13	2.44	-12.61	-5.17	113.3	10.6	-38	-3.6
Scenario6:	Improved refractories for clinker making	52.17	4.86	-89.97	-18.49	27.6	2.57	-107.7	-41.86
Scenario 7:	Indirect firing for clinker making	3.93	00.37	67.57	184.11	8.5	0.8	77.2	97.46
Scenario 8:	Kiln combustion system improvements	16.4	1.53	-38.09	-24.9	35.4	3.3	-55	-167
Scenario9:	Optimized heat recovery upgraded clinker cooler	6.56	0.0.61	-46.77	-76.44	14.1	1.3	-65.5	-49.63
Scenario 10:	Replacing vertical shifts with suspension preheater	52.27	4.88	69.3	14.2	297.1	10.6	77.3	7.31

The results of the analysis both in terms of GHG mitigation potential and associated costs are shown in the emissions reduction cost curves (Figure 3-11 and Figure 3-12). In the cost curves, the horizontal axis shows the cumulative emissions reduction and the vertical axis shows the cost of emissions reduction in terms of CAD per tonne CO_2 reduction. In other words, the width of the bars represents the cumulative mitigation potential and the height shows the associated costs (incremental NPV/tonne CO_2 reductions). For the bars below the horizontal axis, the GHG mitigation cost is negative and for those above the horizontal axis, there is a cost associated with implementing the options.

As shown in Figure 3-11, by 2030, the projected GHG mitigation potential in the Canadian cement industry is 27.3 Mt CO_2eq. In terms of economic performance, slightly more than 74% of the overall emissions reduction is achievable with negative cost (i.e., the cost of implementing the energy saving option is less than the achievable revenues associated with it).

The GHG mitigation potential of different options ranges from 0.37 Mt CO_{2eq} for indirect firing for clinker making to more than 8 Mt CO_{2eq} for blended cement. The GHG mitigation cost fluctuates between -536 $/ Mt CO_{2eq} for adjustable speed drive for kiln fan and 184 $/ Mt CO_{2eq} for indirect firing for clinker making.

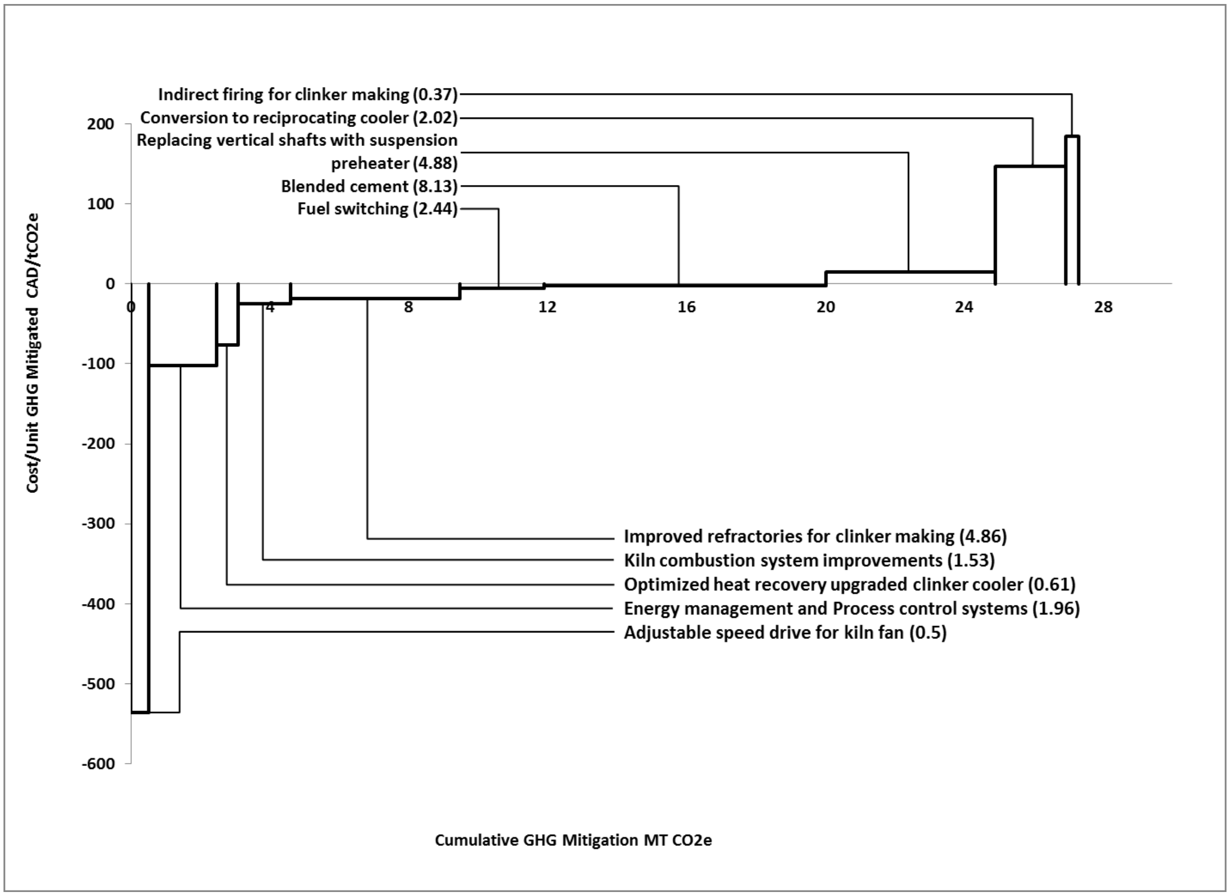

Figure 3-11: Carbon abatement cost curve (fast penetration scenario, 2010-2030)

For the slow penetration scenario, the total achievable emissions reduction is 56.4 $MTCO_2$eq. . Use of alternative feedstock and fuel and replacing the vertical shafts with suspension preheaters are the biggest contributors to GHG emissions reduction. In terms of the GHG mitigation cost, more than 72% of emissions reduction is achievable at a negative cost (Figure 3-12).

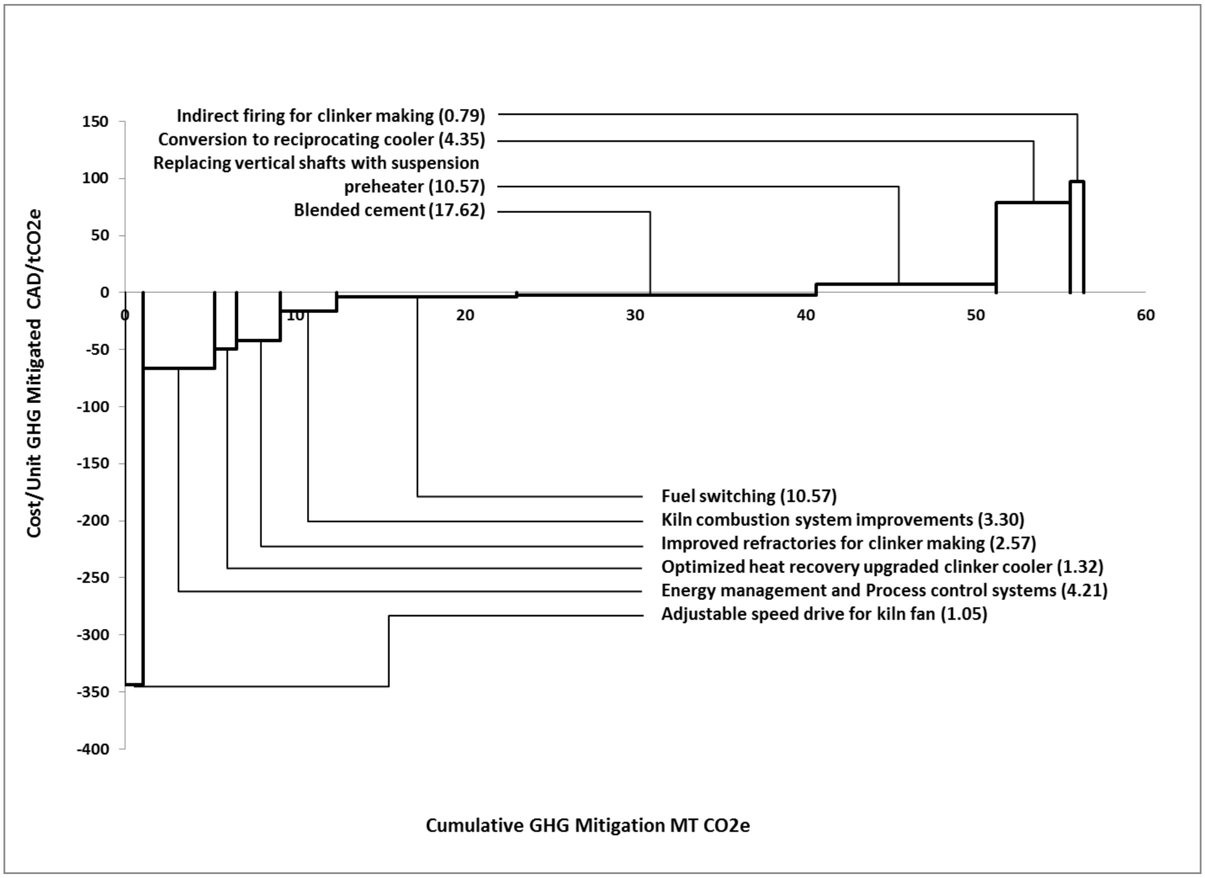

Figure 3-12: Carbon abatement cost curve (slow penetration scenario, 2010-2050)

From the results of both the fast and slow penetration scenarios, the identified energy saving options can be classified into three different categories: revenue generating, cost neutral, and costly options. The revenue-generating options are those in which the associated fuel saving cost would not only compensate the capital and O&M costs but also result in further savings that could be regarded as additional revenue for the industry. Among the options are easily implementable ones such as energy management, advanced control system, and process heat recovery. The implementation of adjustable speed fans is also an economically attractive option that, despite the comparatively low energy saving and GHG saving potential, is the most economically attractive.

The second group of options is categorized as cost neutral (i.e., the GHG mitigation cost is fluctuating around zero CAD/tonne CO_2eq.). Options in this group can be broadly categorized as fuel switching and alternative feedstock. The use of low-carbon fuels such as natural gas and renewables (rather than coal and coke) would not only reduce the emissions intensity of the process but also are economically attractive, considering the low cost and ample availability of natural gas and renewables in Canada. Similarly, the use of additives/different feedstock such as steel slag, fly ash, and kiln dust will not only reduce emissions and save energy in the cement industry but will also help use the low-value products from other industries (such as iron and steel). This is even more important when considering the geographical location of the cement and iron and steel industries (Canada's eastern provinces are the industrial hub for both).

In both the fast and slow penetration scenarios, less than 30% of the overall GHG mitigation potential is costly; and the implementation of the options in this category will impose considerable costs to the system. More precisely, for this group of options, the cost of emissions reduction is from 147 CAD/tonne CO2eq to 184 CAD/tonne CO2eq and 78 CAD/tonne CO2eq to 97 CAD/tonne CO2eq in the fast and slow penetration scenarios, respectively.

3.4. Conclusion

In this study, the current status of the industry was analyzed. The results of the analysis suggest that despite historical improvement in the energy intensity of the cement production process, the Canadian cement industry is less efficient than the global average and there is considerable potential for GHG mitigation. In order to conduct a bottom-up scenario analysis, a detailed data-intensive model was developed in the LEAP model. The applicability of the globally available energy efficiency options for the Canadian industry was assessed, and ten technologies were chosen for scenario analysis. Scenario analysis was done for the 2030 and 2050 time horizons (representing the fast and slow penetration of the technologies). The achievable GHG mitigation was assessed to be 27 and 56 Mt CO_2eq in the time horizons of 2030 and 2050, respectively.

Based on their economic performance, the energy efficiency technologies are classified in three different categories: economically attractive, cost neutral, and costly options. Options such as implementing energy management systems and heat recovery provide the lowest GHG mitigation cost. Fuel switching and the use of alternative feedstock are found to be almost cost neutral and result not only in emissions reduction but also in the use of less-valued co-products from other industries, i.e., iron and steel factories. The third category of options are those that overall impose cost to the system. Replacing vertical shafts with suspension pre-heaters, conversion to reciprocating coolers and indirect firing for clinker making belong to this group of technologies. In terms of the economic performance of the energy saving options, the results suggest that in both the fast and slow pentation scenarios, more than 70% of emissions reduction is achievable with negative costs.

In summary, the results of the analysis suggest that the cement sector could play an important role in helping Canada reach its ambitious emissions reduction targets. While in the short and medium term the GHG mitigation options in categories 1 and 2 (e.g., energy management, heat recovery, fuel switching, and feedstock change) are economically attractive, the economic performance of process modification options (i.e., category 3) will improve in the long term.

Chapter 4 : Potential for energy efficiency improvement and greenhouse gas mitigation from Canada's iron and steel industry

4.1. Introduction

Between 2000 and 2015, annual global steel production increased by more than 89% and reached 1.62 billion tonnes [283, 284]. In 2012, the industry was responsible for 22% and 31% of global industrial energy use and CO_2 emissions, respectively [285]. In other words, with 2.3 Mtonne CO_2 eq. emissions, iron and steel is the largest industrial source of emissions [286-288]. The global steel production level is projected to reach 2.2 billion tonnes in 2050 [289], which will result in an increase of 100% in the industry's GHG emissions [286]. It is expected that fossil fuel based energy consumption will remain the main source of GHG emissions in the iron and steel industry. In addition, as energy accounts for 20-40% of steel production costs [283], saving energy will play an important role in ensuring the economic competitiveness of the industry [290].

Despite high levels of energy consumption, the iron and steel industry is one of the pioneer industries for energy efficiency improvement, and the energy intensity (energy consumption per unit production) of steel production has shown continuous improvement over time. Between 1960 and 2014, the introduction of technologies and techniques such as oxygen lancing, secondary metallurgy, water cooled walls, ladle furnace, and scrap preheating improved energy efficiency by 60% [233, 283]. While continuous improvement in the energy performance of steel production processes has been observed since the 1760s, the pace differed in different time periods [233]. For example, according to the World Steel Association (WSA), the global intensity of steel production has been almost unchanged in the past decade and there have not been any major changes in the energy and carbon intensities of processes (Figure. 4-1) [291].

The slow energy efficiency improvement of the industry in recent years is in contrast with the considerable potential for improving energy intensity in the iron and steel industry. More precisely, compared to the best available technologies, there is the potential to improve the energy and emissions performance of the industry by about 20% [280]. This potential could be realized by implementing the world's best available technologies [292] or by applying alternative iron and steel production routes such as smelting and direct reduction technologies [293]. A recent study by the International Energy Agency indicates that there is the potential to improve energy efficiency by 9-18% in the industry [118]. A study by Energetics [294] , however, reports minimum energy efficiency improvements in the integrated and electric arc furnace (EAF) steel production routes of 31% and 47%, respectively.

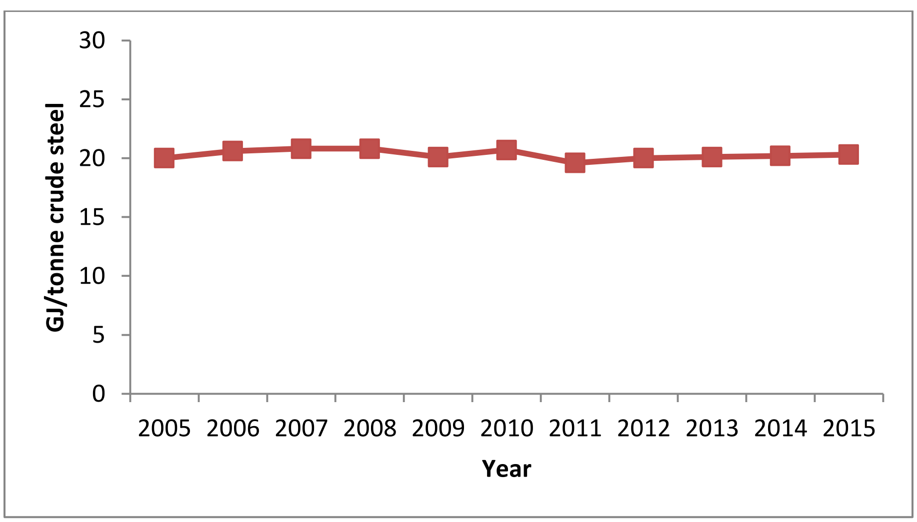

Figure. 4-1: Historical energy intensity of the global steel industry [291]

Several studies use scenario analysis to investigate the long-term energy efficiency improvement and GHG mitigation potential in the iron and steel industry [236, 295]. While in some studies GHG mitigation scenarios were developed to assess the impacts of macro-economic factors such as research and development (R&D), investment trends, and labor productivity on the energy efficiency of the industry [227], others assessed the impacts of policies such as fuel switching and energy efficiency improvement on the long-term emission mitigation potential [228]. This category of studies (i.e., system-level scenario analysis) gives insight into possible future developments in the industry. However, detailed technological requirements to reach the expected energy intensity improvement is not usually used for scenario studies [233]. This is a key gap.

In another set of studies, energy efficiency improvement in the iron and steel industry was investigated from the technology-level perspective. While some studies used a bottom-up approach to identify energy-saving measures [23, 296] or assess their technical applicability [221] and economic feasibility [220], others analyzed the long-term effectiveness of the technologies [297]. In order to assess the economic effectiveness of various energy efficiency measures at the sector-level, energy conservation cost curves were applied in a number of studies [23, 298, 299]. However these studies do not assess the impacts of these technological level improvements over a long term planning horizon and the overall impact on the sector. This is a key gap.

The current research combines scenario analysis and techno-economic assessment techniques to assess the long-term technically feasible emissions reduction potential in the iron and steel industry and address the gaps in the literature as detailed above. In other words, the research synchronizes a bottom-up system analysis, scenario development, and economic techniques to assess the long-term emissions reduction potential from the iron and steel industry. To this end a case study is conducted for the iron and steel industry in Canada.

Canada is the 3rd biggest producer of steel in North America (after the US and Mexico) [283]. The industry accounts for 6% and more than 8% of energy consumption and GHG emissions in Canadian industries, which puts it among the top four biggest industrial energy consumers in the country [234]. The GHG emissions from the industry are expected to increase by more than 25% (compared to the 2010 level) and reach 20 Mtonne CO_2 eq. by 2030, accounting for 12% of industrial emissions[9] [300]. This highlights the importance of GHG abatement strategies in the iron and steel sector to help Canada reach its ambitious GHG mitigation goals.

The specific objectives of the current study are to:

- Analyze the current status of the industry in terms of technological progress, energy consumption, and GHG emissions;
- Identify the major energy-consuming sub-sectors and develop an energy consumption demand tree by using the energy intensity (energy consumption per unit of final product) of each sub sector;
- Analyze various energy-efficiency improvement measures and assess their applicability to the Canadian iron and steel industry;
- Evaluate the long-term energy and environmental impacts and the cost associated with implementing the identified technologies by developing various energy efficiency improvement scenarios in the Long-range Energy Alternative Planning (LEAP) model;
- Develop marginal GHG abatement cost-curves for the Canadian iron and steel industry.

The structure of the chapter is as follows: Section 4.2 describes the overview of the methodology. System analysis, scenario analysis, and economic analysis are discussed in Sections 4.3 to 4.5. Results and discussion are presented in Section 4.6, and Section 4.7 is the conclusion.

[9] Equal to 2% of national emissions.

4.2. Material and methods

4.2.1. The Canadian LEAP model

The analysis was done using the Long-range Energy Alternative Planning system (LEAP) [301, 302]. LEAP is an energy policy analysis and GHG mitigation assessment framework developed by the Stockholm Environment Institute. It is an integrated planning tool that can be used to track the energy consumption, production, and extraction of resources in all economic sectors (Figure 4-2). Energy modelling in LEAP provides the opportunity to account for the interaction between different modules within the energy system. More specifically, simultaneous consideration of energy supply, transformation, and distribution and demand sectors helps the energy modeler to account for sectoral development and the progress in the energy system at different levels.

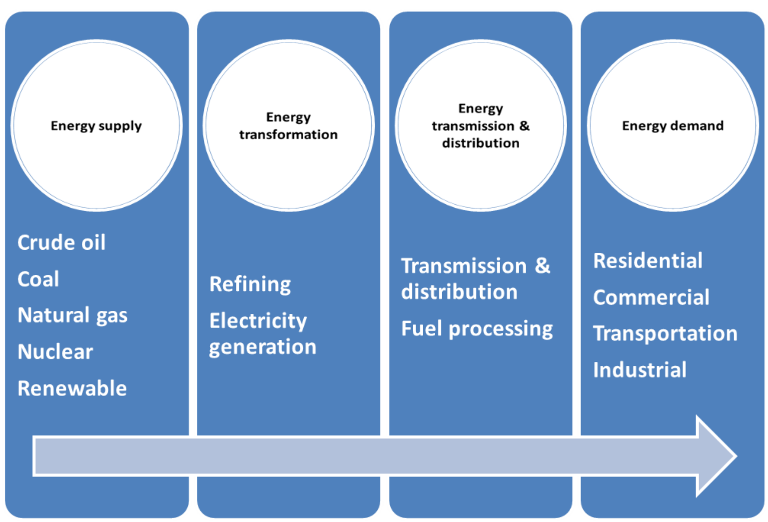

Figure 4-2: Structure of energy system in the LEAP model

The Canadian LEAP model was developed for different provinces and territories using the data from the National Energy Board (NEB), Natural Resources Canada (NRC), Canadian Steel

Producers Association (CSPA), as well as Statistics Canada's CANSIM tables and other similar databases [65].

A detailed model was developed for each province and territory in Canada [61]. On the supply side, province-specific electricity systems (generation, transmission, and distribution) are modelled to represent the electricity supply side, its future development, and the associated emissions factor. While the comprehensive and data-intensive model covers all the stages in the energy system (i.e., resources, transformation, and demand side including residential [62], commercial [63], agriculture [303] and industrial sector [79, 80]), the main focus of this Chapter is the iron and steel production industry.

4.2.2. Demand side energy modeling in LEAP

The main steps in analyzing the long-term GHG mitigation potential in the iron and steel industry are system analysis, scenario development, and cost-benefit analysis. The sub-steps of each phase are shown in Figure 4-3.

In summary, the main steps for the analysis are the assessment of the current status of the industry, the development of the business as usual[10] (BAU) and GHG mitigation scenarios, and the economic analysis.

[10] Also referred to as the baseline scenario in this thesis.

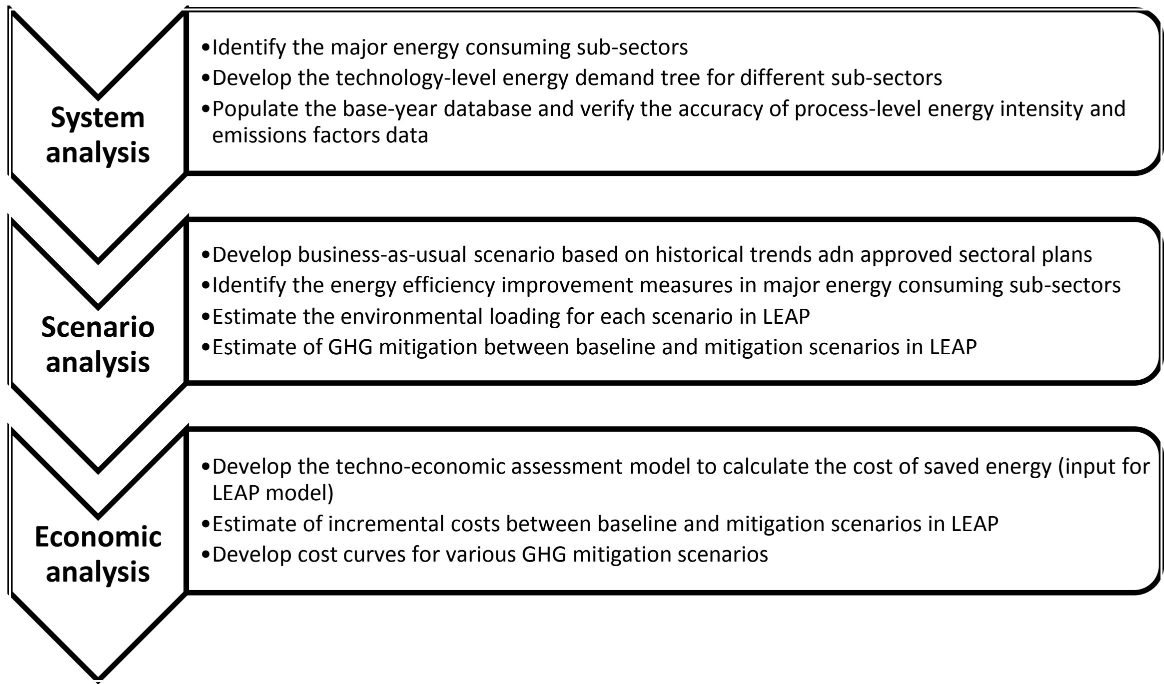

Figure 4-3: Overview of GHG mitigation cost curve methodology

The goal of the system analysis is to identify the major energy-consuming subsectors and develop the energy consumption demand tree. The results of this step will be used to populate the LEAP model database and are the starting point for scenario analysis. In order to assess the mid- to long-term energy saving and GHG mitigation potential from the industry, two sets of scenarios were developed: fast penetration and slow penetration scenarios with time horizons ending in 2030 and 2050, respectively. The BAU scenario was developed as the most probable pathway for future development of the system and serves as the basis for comparison (i.e., the effectiveness of different energy-efficiency measures are assessed by comparing the energy consumption and GHG emissions from various mitigation scenarios and the BAU scenario). Different emissions reduction pathways are assessed in the alternative (i.e., GHG emissions reduction/energy efficiency) scenarios.

In order to assess the economic performance of each option, the cost of saved energy (CSE) and the GHG abatement cost were calculated in the techno-economic model and the LEAP model, respectively. In this way the specific characteristics of the Canadian energy system can be accounted for [79, 304]. In other words, the CSE was calculated by considering the type of fuel used in the iron and steel industry and the Canadian-specific fuel price. The calculated GHG abatement cost not only accounts for the direct emissions reduction in the steel production site (i.e., as a result of fossil-fuel combustion at the steel factory) but also the indirect emissions associated with electricity generation. In the final step of the analysis, incremental GHG mitigation and their associated cost (i.e., the results of the LEAP model) were used to develop the GHG abatement cost curves.

4.3. Process analysis

In Canada, the major pathways for steel production are integrated and EAF[11] production routes, which mainly use iron ore and steel scrap, respectively, as feedstock [111, 305-307]. A simplified schematic of the integrated EAF and steel production routes is shown in Figure 4-4 [111, 306, 307]. Other steel production routes, such as direct reduction and smelting, are not considered, as their share in Canadian steel production is negligible. The sub-processes are described in Appendix III-I.

[11] Direct reduced iron production in Canada is limited to 0.7 Mt.

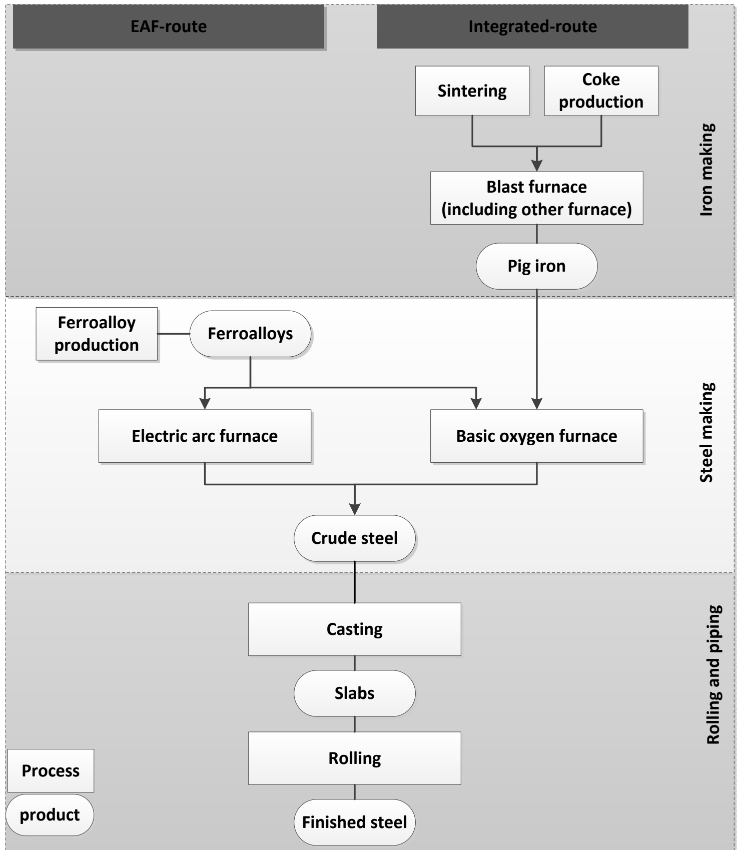

Figure 4-4: Different steel production routes [287]

Integrated plants produce steel from iron ore in blast furnaces and basic oxygen furnaces (BOF). In a blast furnace, iron ore, coal, and limestone are used to produce molten iron. In a BOF, the molten iron and small amounts of scrap steel (up to 30%) are transformed into liquid steel that will be cast into slabs and billets for further processing. EAF plants produce steel by melting steel scrap in the electric arc furnace. The primary raw material for the process is recycled scrap steel that is reheated, purified, and re-cast in the EAF and then sent to billets and slabs for further processing [308].

Although the steel recycling rate in Canada is reported to be between 40% and 60% [111, 306], the historical share of the EAF route in total steel production has been around 40% [118, 305, 309]. There are four integrated plants in Canada with an overall production capacity of 9 million tonnes per year. The steel produced in Ontario basically provides the raw material to the auto industry, whereas the western Canadian steel industry is mostly oriented to meet the needs of the oil, gas, and other resource industries [310].

4.3.1. Energy consumption analysis

The total energy consumption in the Canadian iron and steel industry in 2016 was slightly more than 221 PJ. The breakdown by energy type is shown in Table 4-1.

Table 4-1: Energy consumption in the Canadian iron and steel industry in 2016 (TJ) [199]

Type of Energy	PJ
Electricity	29324
Natural gas	66748
Heavy fuel oil	1709
Middle distillates	1209
Propane	47
Petroleum coke	74
Coal	8336
Coal coke	85307
Coke oven gas	28345
Total	22100

Despite some fluctuations, the energy intensity of the Canadian iron and steel industry has not shown a noticeable change in the past 25 years (Figure 4-5).

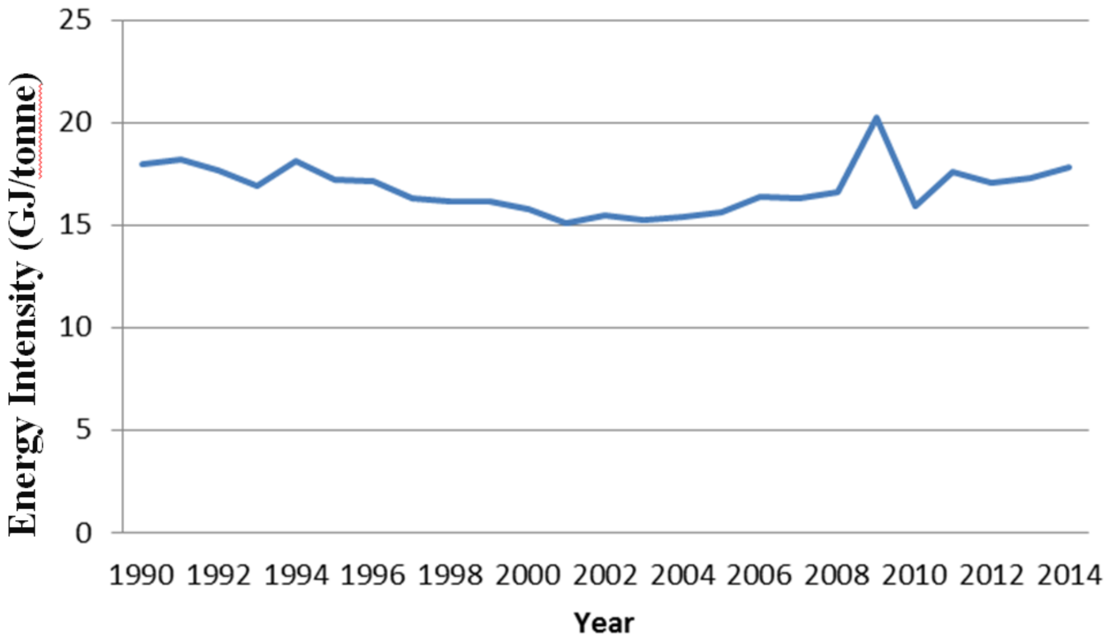

Figure 4-5: Historical energy intensity of the Canadian iron and steel industry [199, 234]

In the steel industry, different types of primary and secondary energy are used as both energy source and reducing agents (

Table 4-2). Both the energy consumption per tonne of steel produced (i.e., energy intensity) and the type of energy carrier vary depending on the steel production route. More precisely, energy consumption in an integrated plant is approximately 2.2-2.6 times higher than in an EAF plant [111, 311, 312], mainly because of the need for more chemical energy, which is used to reduce iron ore to iron [228, 313, 314]. Also, due to differences in feedstock type (i.e., in an integrated plant, feedstock is at least 70% iron ore and up to 30% recycled steel, whereas the main feedstock for an EAF is recycled steel), the type of energy consumed differs considerably [315]. In general, blast furnaces, coke plants, electric arc furnaces, and finishing processes are the most energy-intensive sub-processes in the iron and steel industry.

Table 4-2: Application of energy inputs in steel production [314, 316, 317]

Source of energy	Application as energy	Application as reducing agent
Oil	Steam production	BF Injection
Natural gas	Furnaces	BF Injection, DRI production
Electricity	EAF, rolling mills, and various other motors	-
Coal	-	Coke production, BF pulverized coal injection, DRI production

4.3.1.1. Energy intensity analysis

In order to assess the energy intensity of the steel production industry, we analyzed the intensity of each sub-process. More precisely, the energy intensity of each sub-sector was assessed by conducting a comprehensive literature review (

Table 4-3). The data from the literature were used to develop the demand tree and validate the assumptions (i.e., process-level energy intensity) using the industry's historical energy consumption and GHG emissions [234]. In summary, the energy intensity analysis was done in three steps: a) the energy intensity of sub-processes was analyzed (i.e., the energy consumption demand tree was developed) b) the process energy intensity was aggregated and the systems-level energy consumption was calculated (in the LEAP model), and c) the model was validated using the systems-level data available in the public domain.

Table 4-3: Energy intensity of different sub-sectors in the iron and steel industry [25, 83, 111, 221, 318-321][12]

Sub-sector	Process	Integrated route		EAF route	
		Electricity (GJ/tonne crude steel)	**Fuel (GJ/tonne crude steel)**	**Electricity (GJ/tonne crude steel)**	**Fuel (GJ/tonne crude steel)**
Iron Making	Sintering	0.20	2.29	NA	NA
	Coke making	0.23	5.23	NA	NA
	Iron making	0.08	12.26	NA	NA
Steelmaking	BOF steelmaking	0.09	0.78	NA	NA
	EAF steelmaking	NA	NA	1.98	0.81
Rolling and Finishing	Vacuum degassing and ladle metallurgy	0.13	0.35	0.40	0.12
	Continous casting	0.12	0.00	0.12	0.00
	Ignot casting	0.65	1.41	NA	NA
	Slab mill	0.42	2.14	NA	NA
	Hot rolling (inc. reheating)	0.33	1.74	1.19	0.76
	Hot dip galvanneal	0.93	2.33	0.79	1.16

4.3.1.2. Energy consumption demand tree

The energy intensity and the type of energy carrier used in the major energy consuming subsectors were used to develop the energy consumption demand tree (Figure 4-6). As shown in the figure, there are three major steps in the steel production process: iron making, steelmaking, and finishing.

[12] For each data point in the table, data were acquired from different sources, harmonized and selected to represent the Canadian iron and steel industry.

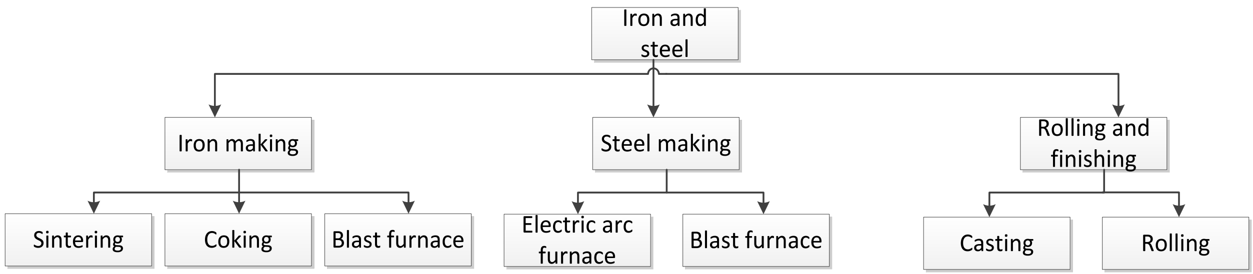

Figure 4-6: Energy demand tree for the iron and steel sector

4.3.1.3. Model verification

The energy intensities of the different sub-sectors in the energy consumption demand tree together with the historical production data were used to validate the model. The LEAP model was validated for the years 2004-2012. The factors are used for model verification include:

- Steel production: Data on the physical production of steel [283].
- The shares of different routes (i.e., the integrated route vs. the EAF route): the historical shares of the BOF and EAF routes were adopted from the Canada-specific published data [283].
- The capacity load of each sub-process: the shares of the final products were estimated [283] and the efficiency of different processes was considered to be similar to the plants considered in the literature [83].
- Emissions factors: for fossil fuel combustion, the Intergovernmental Panel on Climate Change (IPCC) Tier 1 default emission factors available in the Technology Environmental Database in the LEAP model were used. The emission factors of the electricity sector were based on the detailed supply side model developed for different Canadian provinces and considering future development of the system. More precisely, depending on the location of the iron and steel factory, the emissions factors for electricity consumption and production differ, and this is accounted for in modelling.

The results of model verification for system-level energy consumption and GHG emissions are shown in Figure 4-7 and Figure 4-8, respectively.

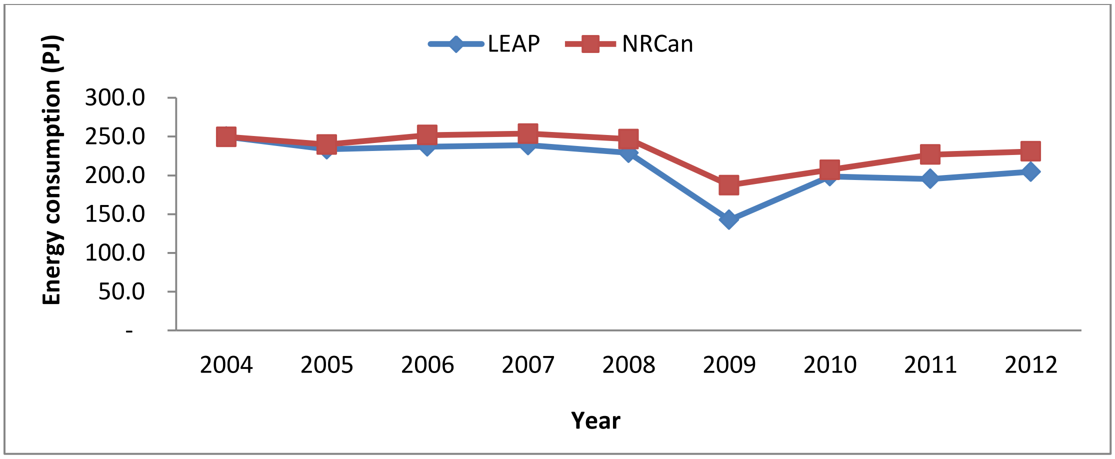

Figure 4-7: Historical energy consumption in the Canadian iron and steel industry (model verification)

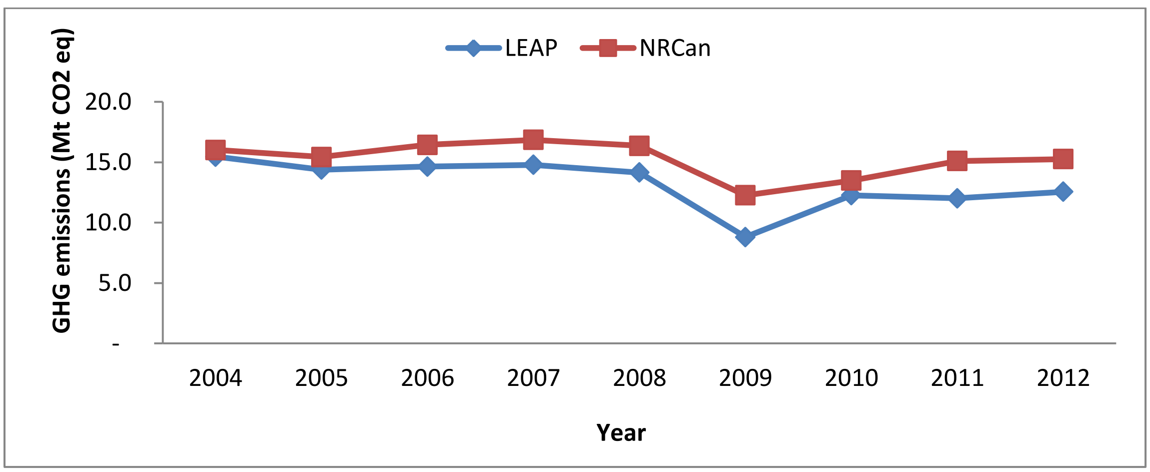

Figure 4-8: Historical greenhouse gas emissions in the Canadian iron and steel industry (model verification)

As shown in Figure 4-7 and Figure 4-8, the results of the LEAP model are in line with the actual data reported by Natural Resources Canada (NRC), thereby confirming the validity of assumptions for the energy and emissions intensities of different sub-processes in the iron and steel industry and also enhances the reliability of the model for scenario analysis.

4.4. Scenario analysis in the LEAP model

4.4.1. Baseline scenario

The following assumptions were made in developing the baseline scenario:

- 2010 is considered the base year for study. Real-world data from 2010 for the physical production of iron and steel and actual consumption of different energy carriers were used to populate the base-year database in the LEAP model. Where applicable, real-world data were used for the subsequent years.
- The energy intensity of the processes was considered to be constant during the time period of the study. This is in line with both historical trends in the Canadian iron and steel industry and experts' opinions [199, 234, 311, 322].
- The long-term steel production in different provinces in Canada was calculated to be similar to the data shown in Figure 4-9. A detailed methodology that we developed to predict future steel production is provided in Appendix III-II.

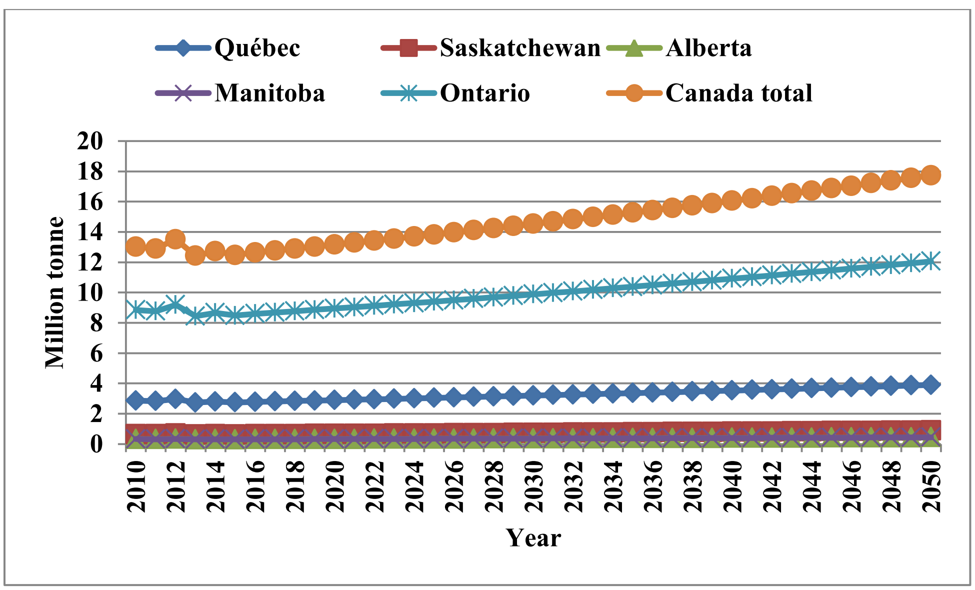

Figure 4-9: Projection of steel production in Canada and in various provinces

To calculate the production shares of each steel production route, a combination of historical trends and market analysis was used. Over the past 14 years, the share of EAFs in Canada's total steel production has not changed much; it has remained constant at around 40% [199]. However, following the trends in pioneering countries, the situation is expected to change in Canada. More qprecisely, in their study, Arens et al. indicate that 75% of specific energy consumption (SEC) improvement in the German iron and steel industry between 1991 and 2007 was due to the shift from integrated to EAF steel production [287]. In China it is expected that there will be similar structural changes toward vast application of EAF [286]. The increasing EAF use is due to the high flexibility of the technology in producing low to high alloyed steel grades, the range of insertable input materials, and the lower energy consumption compared to integrated plants [323]. In addition, for the case of Canada, an EAF is a favorable option because of the lower capital cost compared to integrated plants, the abundance of natural gas, and the restrictions in the use of coal (i.e., for coke production) imposed by the government [177, 178]. In addition, Ontario as the biggest steel producer in the country has always had a scrap surplus [310] and therefore, EAFs are expected to be favored in that province [286].

Nevertheless, there are some limitations that restrict the vast application of EAF technology. The lack of a appropriate quality of steel produced from salvaged scrap [111], the long lifetime of steel products, and the slow recycling rate of steel, along with increasing demand for steel products, highlight the need for a combined use of primary (i.e., integrated route) and secondary (i.e., EAF) steel production methods [314].

Based on the above justifications, for this study, it is considered that in Canada the capacity of integrated plants will remain constant over the time period of the study and the additional capacity would be solely through EAFs.

4.4.2. Alternative scenarios

Literature review found examples of efforts to improve energy efficiency in the iron and steel industry. For example, in the past two decades, SEC improvements in Germany were 0.4% per annum. Energy efficiency improvement was the biggest contributor to SEC in the industry, with rolling and blast furnace showing the largest improvements of 1.4 and 0.2% [287]. In a blast furnace (BF), SEC improvement was in BF gas recovery [287]. Similarly, in the US, historical trends show that in a period of 20 years, the SEC of integrated plants improved by more than 40% [311] and there were opportunities to improve energy efficiency by as much as 18% more [221]. Unlike the basic oxygen furnace and the blast furnace, the SECs of sinter plants and EAFs were constant or changes were negligible [287, 311].

In order to develop alternative scenarios for the Canadian steel industry, we identified the globally available energy saving options. We then analyzed the applicability of the identified options for the Canadian industry and assessed their technical performance, their associated costs, and the penetration potential of each technology. Extensive literature review was conducted for data acquisition and development.

For the purpose of the current study, only the technological improvement options that fall within the specified system boundary (as illustrated in Figure 4-4) were analyzed; the general non-process-specific energy efficiency options are considered to be beyond the scope of this study. In other words, energy saving options in the coking plant, sintering plant, BF, steel workshop (both BOF and EAF), and finishing processes were considered. To identify energy efficiency measures, we compared the existing Canadian technologies with EcoTech and the best available mature technologies worldwide [111, 324] and subsequently identified the areas of improvement.

Of the 113 identified energy efficiency technologies [280], 26 were selected for the analysis. The criteria used to screen the options include technology readiness level, applicability to the Canadian iron and steel industry, and availability of data. In terms of development status, only commercially available technologies were considered. The applicability of the technology to the Canadian iron and steel industry was assessed based on the current and expected development status of the industry. For example, in the material preparation stage, the energy efficiency measures for pelletizing plants were excluded because, based on review of Canadian industry, all of the iron production plants in the country are equipped with sintering plants rather than pelletizing plants. As another example, in Canada, continuous casting technology could be implemented in only 3% of the plants because 97% of these are already equipped with the technology [283]. The injection of coal in blast furnaces was not considered because of national and provincial limitations on coal consumption as well as the cheap price and abundant availability of natural gas in Canada. In general, wherever data are available for Canada, country-specific limitations were considered when choosing the technologies. Otherwise, due to similarities between Canada and the United States, the applicability of energy efficiency measures was considered to be comparable in the two countries and US data were used. The selected technologies can be categorized to cover different sub-sectors within the industry (as shown in the energy consumption demand tree) and are summarized in

Table 4-4.

Table 4-4: List of energy efficiency measures applicable to the Canadian iron and steel industry [23, 221, 280, 318]

Technology/ measure	**Description**
Sintering	
Heat recovery from the sinter cooler	The waste heat from a sintering plant is generally classified as sensible heat from either the main exhaust/sintering machines or the sinter cooler. In order to avoid unacceptable condensation and corrosion, the only practical method for heat recovery from process gases is to transfer sensible heat directly to the sinter bead by hot gases (i.e., waste gas recirculation). However, the heat from the sinter cooler could be recovered through steam generation in the waste gas boiler, hot water generation for district heating, preheating combustion air, preheating the sinter raw mix, or using the waste heat in a recirculation system.
Improved process control	The application of numerical/simulation models and automated control systems will help improve operational parameters and optimize energy consumption, productivity, and safety.
Use of waste fuels in sinter plants	Waste material such as oil from the cold rolling mills could be used as a source of energy (substituting coke breeze). This will impact the emissions of air pollutants and organic compounds. The application of oil might be limited by the permitted emissions limit and may also depend on existing emission control systems. The energy content of the waste fuel is another factor affecting the rate at which these materials are used.
Coke making (in the steel industry)	
Coal moisture control	The heat from the coke oven gas could be used to reduce the moisture content of coal from the normal 8-10% to 6%. The reduced moisture content of the coal will improve coke quality and reduce the carbonization energy (heat)
Automation and process control system	Programmed heating (as opposed to the conventional continuous heating) of coke oven will optimize the supply and use of fuel. It also stabilizes the operation of the coke battery and therefore prolongs battery life and improves coke quality.
Coke dry quenching (CDQ)	Using inert gas instead of the traditional sprayed water reduces energy loss in the quenching process. The thermal energy in the quenching gas can be recovered and used to produce steam and electricity or preheat the coking coal.
Iron Making — blast furnace	
Injection of natural gas in the BF	In this process, natural gas is used instead of coke in the blast furnace. The hydrogen content of natural gas acts as the reducing agent and therefore reduces the formation of carbon dioxide. It is technically feasible to retrofit existing plants, and capital investment for this is minimal. The technology is attractive where natural gas is cheap.

Technology/ measure	Description
Improved recovery of BF gas	The gases leaving the BF contain almost 30% of the heat content of the gross energy consumption in the blast furnace. This energy could be recovered and used as fuel or for electricity generation after being enriched by coke oven gas or natural gas.
Improved hot stove process control	The operation of hot stoves could be maintained close to optimum conditions by implementing automatic control. Automatic control will not only help minimize the fuel consumption but also maximize the reliability and lifetime of the stove.
Recuperator hot blast stove	The recovery of the flue gases from the blast stove (with typical temperatures of around 250°C) will improve the efficiency of the stove. This heat, together with the heat from sinter cooling, can be used to preheat the fuel and the air entering the stove.
Improved blast control systems	Different parameters such as the rate of the reducing agent can be controlled. Using different parameters, such as burden control and distribution, mass and energy balance, and silicon prediction, etc., will help diagnose the process disturbance and therefore make it possible to change the process parameters to optimize performance.
Steelmaking – BOF basic oxygen furnace	
Efficient ladle preheating	Ladle preheating is estimated to use 0.02 GJ/t steel. This could be lowered by using temperature control technologies, installing hoods, or reducing preheating needs with recuperative and oxyfuel burners.
Hot Rolling	
Hot charging	In the still plants where caster and reheating furnaces are located near one another, charging the slabs in the reheating hot-rolling furnace is possible. Hot charging not only reduces energy consumption but also improves the productivity and quality of the products.
Process control in hot strip mills	In the hot strip mill, when combustion is optimized, the downtime of the process and therefore the energy consumption will decrease.
Recuperative burners	In principle, the recuperator is a gas-to-gas heat exchanger that transfers the heat from exhaust gas to the combustion air. The performance of modern recuperatives is noticeably higher than the older technologies and thus replacing them will save energy through more efficient pre-heating of the combustion air.
Insulating furnaces	Replacing conventional insulating materials with ceramic low thermal mass insulation materials can reduce the heat losses through furnace walls.
Controlling oxygen levels and VSDs on combustion air fans	The technique helps optimize combustion in the furnace by controlling the flow of combustion air and oxygen levels and therefore maximizing combustion efficiency.
Energy-efficient drives (rolling mill)	Energy-efficient drives can replace the currently used AC drives, thereby saving energy.

Technology/ measure	Description
Waste heat recovery (cooling water)	Absorption heat pumps could be used to recover the heat from the cooling water, which is sprayed on rolled steel. The technology is particularly attractive where the generated low-pressure steam could be used on site.
Adopt continuous casting	As the intermediate storage and therefore the need for reheating is eliminated in continuous casting, it uses much less energy than the ingot casting process. The product of the ladle process (i.e., liquid steel) flows to the holding tank where it will be ultimately solidified in a water-cooled copper mold and continue through the caster.
Steelmaking – EAF	
Improved process control (neural network)	Modern process control systems in the EAF integrate real-time monitoring of process variables (e.g., temperature, carbon level, etc.), and by optimizing the process, significantly reduce electricity consumption.
Flue gas monitoring and control	By using optical sensors and monitoring the furnace exhaust gas flow rate and composition, it will be possible to investigate the post-combustion off-gases and optimize their operation and chemical energy recovery. This will help reduce energy consumption considerably.
Transformer efficiency — UHP transformers	The installation of new transformers or paralleling existing transformers will make it possible to convert the furnace operation to high power or even ultra-high power (UHP). UHP operation will reduce energy losses, which are as high as 7%, of transformer losses in conventional transformers.
Foamy slag practice	Foamy slag is obtained by injecting carbon (granular coal) and oxygen or by lancing the oxygen only. The foamy slag is used to cover the ark and melt surface, which minimizes the radiation heat losses.
Bottom stirring/stirring gas injection	The injection of inert gases in the bottom of the EAF improves heat transfer and also the yield of liquid metal. The applicability of the technique is limited to the furnaces where oxygen is already injected in the furnace.
Electric bottom tapping	Electric bottom tapping will result in several improvements in the process including reducing the electrode consumption, reducing the tap-to-tap time, and increasing the ladle life.

For both the fast and slow penetration scenarios, it was considered that the energy efficient technologies would reach their maximum penetration potential by the end of the study period. For example, if the current and maximum penetration potentials of an energy efficiency technology are 0% and 70%, respectively, it was considered that the 70% penetration potential would be realized during the time horizon of the study following a linear trend. As the base for comparison, a baseline scenario was developed for both time periods of the study.

4.5. Economic analysis

4.5.1. Technological performance

The techno-economic performance of the energy efficiency options in terms of energy savings potential and their associated costs (both capital and O&M costs) are summarized in Table 4-5. Data in Table 4-5 are taken from different sources (mainly from Worrel et. al., 2011 [325], Hasanbeigi et. al., 2013 [23], Institute for Industrial Productivity Database [280]). The costs were then harmonized to 2010 CAD (using discount rates and different currency exchange values). and the penetration values were calculated based on specific characteristics of the Canadian iron and steel industry (Section 4.4.2).

Table 4-5: Techno-economic performance of energy efficiency options

No.	Energy Efficiency Options	Fuel saving	Electricity saving	Cost (CAD$ /tonne)		Life time (years)	Penetration potential (%)
		(GJ/tonne steel)	(GJ/tonne steel)	Retrofit Cap. cost	Changes in O&M		
1	Adopt continuous casting	0.24	0.08	12.31	-5.49	20	3%
2	Automation and process control system (coke making)	0.05	0	0.07	0.00	10	90%
3	Bottom stirring/stirring gas injection	0	0.07	0.62	-2.06	0.5	11%
4	Coal moisture control	0.09	0	15.14	0.00	10	70%
5	Coke dry quenching	0.37	0	21.63	0.15	18	70%
6	Controlling oxygen levels and VSDs on combustion air fans	0.29	0	0.45	0.00	10	50%
7	Electric bottom tapping (EBT) on	0	0.05	3.30	0.00	10	52%

No.	Energy Efficiency Options	Fuel saving	Electricity saving	Cost (CAD$ /tonne)		Life time (years)	Penetration potential (%)
		(GJ/tonne steel)	(GJ/tonne steel)	Retrofit Cap. cost	Changes in O&M		
	existing furnace						
8	Efficient ladle preheating	0.02	0	0.05	0.00	30	90%
9	Energy-efficient drives (rolling mill)	0	0.01	0.18	0.00	20	50%
10	Flue gas monitoring and control	0	0.05	2.06	0.00	10	50%
11	Foamy slag practice	0	0.07	10.31	-1.85	10	30%
12	Hot charging	0.52	0	13.49	-1.19	10	36%
13	Improved blast control systems	0.36	0	0.33	0.00	10	60%
14	Improved hot stove process control	0.33	0	0.28	0.00	10	50%
15	Improved insulation of reheating furnace	0.14	0	9.00	0.00	10	30%
16	Improved process control (sintering)	0.01	0	0.03	0.00	10	100%
17	Improved process control (neural network)	0	0.11	0.98	-1.03	10	90%
18	Improved recovery of blast furnace gas	0.06	0	0.28	0.00	15	60%
19	Injection of natural gas to 140 kg/thm	0.8	0	4.60	-1.83	20	70%
20	Process control in hot strip mill	0.26	0	0.63	0.00	10	69%
21	Recuperative burners	0.61	0	2.25	0.00	10	20%
22	Recuperator hot blast stove	0.07	0	1.29	0.00	10	30%
23	Sinter plant heat recovery	0.12	0	0.68	0.00	10	100%
24	Transformer efficiency — UHP transformers	0	0.06	2.83	0.00	15	40%
25	Use of waste fuels in sinter plant	0.04	0	0.04	0.00	10	90%
26	Waste heat recovery (cooling water)	0.03	0	0.72	0.06	15	69%

4.5.2. The cost of saved energy

The cost of saved energy is defined as the cost to reduce one unit of energy consumption (e.g., CAD/GJ). The cost of saved energy (CSE) is calculated in a techno-economic model using the factors outlined in Table 4-6.

Table 4-6: The input data for techno-economic modeling

Capital cost	The capital cost is the capital investment associated with implementing the technology. The investment happens at the implementation time of the technology and happens again at the end of the technology's lifetime.
O&M cost	Operation and maintenance costs are those related to the operation of the plant. The costs include the labor and regular maintenance costs that are required to maintain the operation of the plant. Both fixed and variable costs are considered. While the former remains constant during the production of products, the latter varies with the production level.
Fuel saving cost	The fuel saving cost/revenue is the revenue associated with reducing energy consumption. In other words, the implementation of each energy efficiency measure will reduce the amount of energy consumption in specific processes, which will accordingly reduce the overall costs of the production process.

Equation 4-1 is applied to calculate the cost of saved energy.

$$CSE = \frac{\sum(C_{EE} - C_{Base}) + \sum(O\&M_{EE} - O\&M_{Base}) + \sum(F_{EE} - F_{Base})}{\sum EC_{Base} - EC_{EE}}$$ **Equation 4-1**

As shown in the equation, capital cost (C), operation and maintenance cost (O&M), and fuel saving cost/revenue (F) together with the energy consumption (EC) of both existing (base) and energy-efficient (EE) technologies are used to calculate the CSE. For the analysis, a discount rate of 5% and inflation rate of 2% are considered and fuel prices are adopted in the literature [79]. We used the weighted average of the fuel price for the provinces in which steel is produced. The results of techno-economic assessment and the costs of saved energy are summarized in Table 4-7 and are used as inputs in the LEAP model.

Table 4-7: Costs of saved energy (CAD/GJ) by scenario

Scenario No.	**Energy-efficiency improvement scenarios**	**Time period**			
		2010-2020	**2020-2030**	**2030-2040**	**2040-2050**
Scenario 1:	Adopt continuous casting	-3.82	-4.66	-5.38	-6.19
Scenario 2:	Automation and process control system	-4.03	-5.38	-6.34	-7.54
Scenario 3:	Bottom stirring/stirring gas injection	-24.12	-26.74	-28.71	-31.17
Scenario 4:	Coal moisture control	17.57	16.22	15.26	14.06
Scenario 5:	Coke dry quenching	3.41	2.06	1.10	-0.10
Scenario6:	Controlling oxygen levels and VSDs on combustion air fans	-4.01	-5.37	-6.33	-7.53
Scenario 7:	Efficient ladle preheating	-1.28	-1.56	-1.84	-2.11
Scenario 8:	Electric bottom tapping (EBT) on existing furnace	-15.53	-17.50	-19.96	-15.53
Scenario9:	Energy-efficient drives (rolling mill)	-19.19	-21.77	-23.76	-26.22
Scenario 10:	Flue gas monitoring and control	-16.11	-18.73	-20.70	-23.16
Scenario 11:	Foamy slag practice	-5.81	-8.44	-10.41	-12.87
Scenario 12:	Hot charging	-1.15	-2.51	-3.47	-4.66
Scenario 13:	Improved blast control systems	-4.10	-5.45	-6.41	-7.60
Scenario 14:	Improved recovery of blast furnace gas	-3.61	-4.97	-5.93	-7.12
Scenario 15:	Improved hot stove process	-5.46	-6.42	-7.61	-5.46

Scenario No.	Energy-efficiency improvement scenarios	Time period			
		2010-2020	2020-2030	2030-2040	2040-2050
	control				
Scenario 16	Improved insulation of reheating furnace	4.11	2.75	1.79	0.59
Scenario 17	Improved process control – EAF neural network	-21.51	-24.13	-26.10	-28.56
Scenario 18	Improved process control – sintering	-1.22	-1.49	-1.77	-2.04
Scenario 19	Injection of natural gas to 140 kg/thm	-3.77	-5.12	-6.08	-7.28
Scenario 20	Process control in hot strip mill	-3.90	-5.26	-6.22	-7.42
Scenario 21	Recuperative burners	-3.73	-5.10	-6.06	-7.25
Scenario 22	Recuperator hot blast stove	-0.08	-0.13	-0.15	-0.18
Scenario 23	Sinter plant heat recovery	-0.88	-1.16	-1.44	-1.71
Scenario 24	Transformer efficiency – UHP transformers	-15.33	-17.95	-19.92	-22.39
Scenario 25	Use of waste fuels in the sinter plant	-1.48	-1.76	-2.04	-2.31
Scenario 26	Waste heat recovery (cooling water)	-0.83	-2.19	-3.15	-4.35

4.5.3. GHG abatement cost

The GHG abatement cost (cost per unit of mitigated GHG emissions in CAD/tonne CO_2 eq) is calculated using the net present value (NPV) and the cumulative emissions reduction in each scenario (calculated over the time period of the study). NPV analysis is an established economic assessment technique that takes into account the cash flow of the project (i.e., both costs and revenues) and discounts those values to the implementation year of the project. As shown in Equation 4-2, the cash flow (CF) is discounted using the discount rate (r) for each year (i) over the lifetime of the project (n). For emissions reduction, the cumulative mitigation over the time period of the study (i.e., 2030 and 2050 for the fast and slow penetration scenarios, respectively) is taken into consideration.

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i}$$ **Equation 4-2**

The results of the analysis, including cumulative energy and emissions reduction as well as the NPV and GHG abatement cost for each option, are presented in Section 4.6.

4.6. Results and discussion

An analysis of the baseline scenario shows that the large-scale adoption of EAF technology would lower the energy and GHG intensity of the Canadian iron and steel industry considerably. More precisely, the increased shares of EAF technology (i.e., from 40% in the base year to 52% in 2050) would lower the energy intensity of steel production by slightly more than 11%. This is in addition to the achievable energy intensity improvement through the implementation of energy efficiency measures.

The results of the analysis for both fast and slow penetration scenarios are presented in Table 4-8. In the table, the technological performance of each technology in terms of cumulative energy savings and GHG mitigation is presented. In addition, two different economic parameters are presented to assess the economic competitiveness of each technology. More precisely, while the net present value of the technology provides insight into the long-term viability of investment, by comparing the GHG abatement cost, the comparative economic performance of each technology for GHG mitigation can be assessed.

Table 4-8: Results of the LEAP model

No.	Energy-efficiency improvement scenarios	Fast penetration scenario (2010-2030)				Slow penetration scenario (2010-2050)			
		Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV & GHG abatement cost		Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV & GHG abatement cost	
		Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq.	Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq
1	Adopt continuous casting	0.78	0.03	-0.08	-2.43	1.53	0.06	-0.08	-1.27
2	Automation and process control system	3.66	0.16	-6.24	-38.31	7.18	0.32	-7.46	-23.34
3	Bottom stirring/stirring gas injection	0.47	0.01	-0.36	-29.38	1.24	0.02	-0.59	-38.06
4	Coal moisture control	5.10	0.23	25.7	113.26	10.00	0.44	25.27	56.79
5	Coke dry quenching	21.07	0.94	12.53	13.37	41.30	1.84	7.64	4.16
6	Controlling oxygen levels and VSDs on combustion air fans	19.72	1.10	-31.01	-28.12	44.16	2.47	-44.26	-17.92
7	Efficient ladle preheating	1.45	0.08	-0.83	-10.26	2.84	0.16	-0.88	-5.53
8	Electric bottom tapping (EBT) on existing furnace	1.49	0.04	-3.42	-88.15	3.89	0.05	-5.84	-119.46
9	Energy-efficient drives (rolling mill)	7.39	0.02	-4.31	-286.71	25.88	0.02	-5.67	-258.64
10	Flue gas monitoring and control	1.44	0.04	-3.79	-101.46	3.74	0.05	-6.35	-135.00
11	Foamy slag practice	1.29		-0.91	-27.24	3.37			

No.	Energy-efficiency improvement scenarios	Fast penetration scenario (2010-2030)				Slow penetration scenario (2010-2050)			
		Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV & GHG abatement cost		Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV & GHG abatement cost	
		Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq.	Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq
			0.03				0.04	-1.67	-39.35
12	Hot charging	25.52	1.43	-14.04	-9.84	57.16	3.20	-23.02	-7.20
13	Improved blast control systems	17.60	1.91	-18.38	-9.62	34.51	3.75	-21.70	-5.80
14	Improved recovery of blast furnace gas	2.95	0.32	-2.81	-8.76	5.79	0.63	-3.34	-5.32
15	Improved hot stove process control	13.44	1.46	-11.85	-8.12	26.34	2.86	-13.84	-4.84
16	Improved insulation of reheating furnace	5.69	0.32	2.52	7.93	12.74	0.71	1.92	2.70
17	Improved process control — EAF neural network	5.82	0.15	-34.23	-226.49	15.16	0.19	-56.64	-297.36
18	Improved process control-sintering	0.85	0.09	-0.46	-4.99	1.67	0.18	-0.47	-2.59
19	Injection of natural gas to 140 kg/thm	45.58	4.95	-75.05	-15.17	89.35	9.70	-88.96	-9.17
20	Process control in hot strip mill	24.25	1.36	-51.8	-38.2	54.23	3.03	-74.28	-24.50
21	Recuperative burners	16.52	0.92	-9.89	-10.71	36.96	2.07	-14.27	-6.90
22	Recuperator hot blast stove	1.70		-1.82	-9.86	3.34			

No.	Energy-efficiency improvement scenarios	Fast penetration scenario (2010-2030)				Slow penetration scenario (2010-2050)			
		Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV & GHG abatement cost		Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV & GHG abatement cost	
		Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq.	Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq
			0.18				0.36	-2.27	-6.26
23	Sinter plant heat recovery	9.75	1.06	-3.81	-3.6	19.11	2.07	-4.59	-2.21
24	Transformer efficiency — UHP transformers	1.44	0.04	-2.77	-74.19	3.74	0.05	-4.70	-99.92
25	Use of waste fuels in sinter plant	2.90	0.31	-1.66	-5.29	5.68	0.62	-1.94	-3.15
26	Waste heat recovery (cooling water)	3.02	0.17	-2.72	-16.06	6.84	0.38	-4.45	-11.64

The results of the analysis were used to develop GHG abatement cost curves (GACC) (shown in Figure 4-10 and Figure 4-11). The figures show both the effectiveness of each energy efficiency option in mitigating GHG emissions and their economic performance. The horizontal axis shows the cumulative emissions reduction achievable by implementing each option and the vertical axis represents the associated cost to reduce one unit of the emissions (i.e., CAD/tonne CO_2 eq). In terms of mitigation costs, the options with overall negative cost are below the horizontal axis. For these options, the achievable revenues over the time period of the study exceeds the costs associated with implementing the option. The options with the lowest mitigation cost are on the left side of the figure and the more expensive options are on the right side. The options for which the GHG abatement costs are positive (the costs exceed the revenue over the time period of the study) are shown by the bars above the horizontal axis.

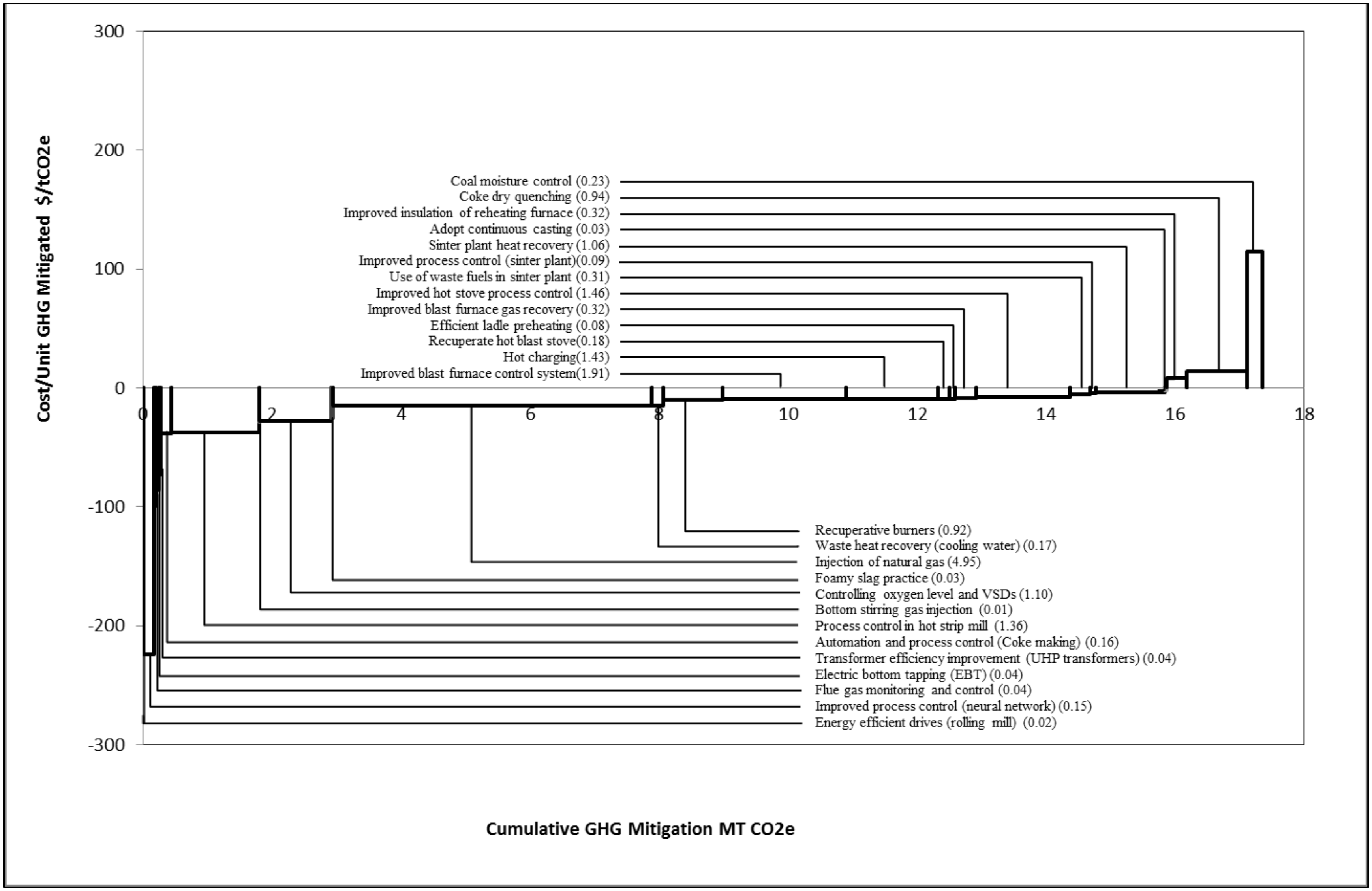

Figure 4-10: Fast penetration scenario GHG emission cost curve (2030 time horizon)

As shown in Figure 4-10, the cumulative GHG mitigation potential that is achievable over the time horizon of 2030 is slightly more than 17 million tonne CO_2 eq. More than 92% of the emissions reduction is achievable with negative cost. The injection of natural gas in the blast furnace provides the biggest mitigation potential with a cumulative emissions reduction potential of more than 4.95 million tonnes (equal to more than 30% of the overall achievable emissions reduction potential). For this option, the GHG abatement cost is calculated to be almost -15 CAD/tonne CO_2 eq, which highlights the economic attractiveness of the fuel switching option. Although there are several options with an abatement cost of less than -25 CAD/tonne CO_2 eq, the implementation of only few of them would result in considerable GHG savings. Among the 10 cheapest GHG mitigation options, only process control in hot strip mills and controlling the oxygen level of combustion air fans would result in cumulative emissions reduction of more than 1 million tonne CO_2 eq. The cumulative emissions reduction of the rest of the options (those among the 10 least expensive) is less than 0.5 tonne CO_2 eq. The GHG abatement costs of more than 66% of the overall achievable emissions are between -15 and -8 CAD/tonne CO_2 eq. Process control in different units and fuel switching are among the most promising options in this group. Heat recovery from the sinter plant and the adoption of continuous casting are almost cost neutral. Among all the options, only the insulation of reheating furnaces, coke dry quenching, and coal moisture control impose costs to the system. The options cumulatively account for less than 10% of the total emissions reduction potential.

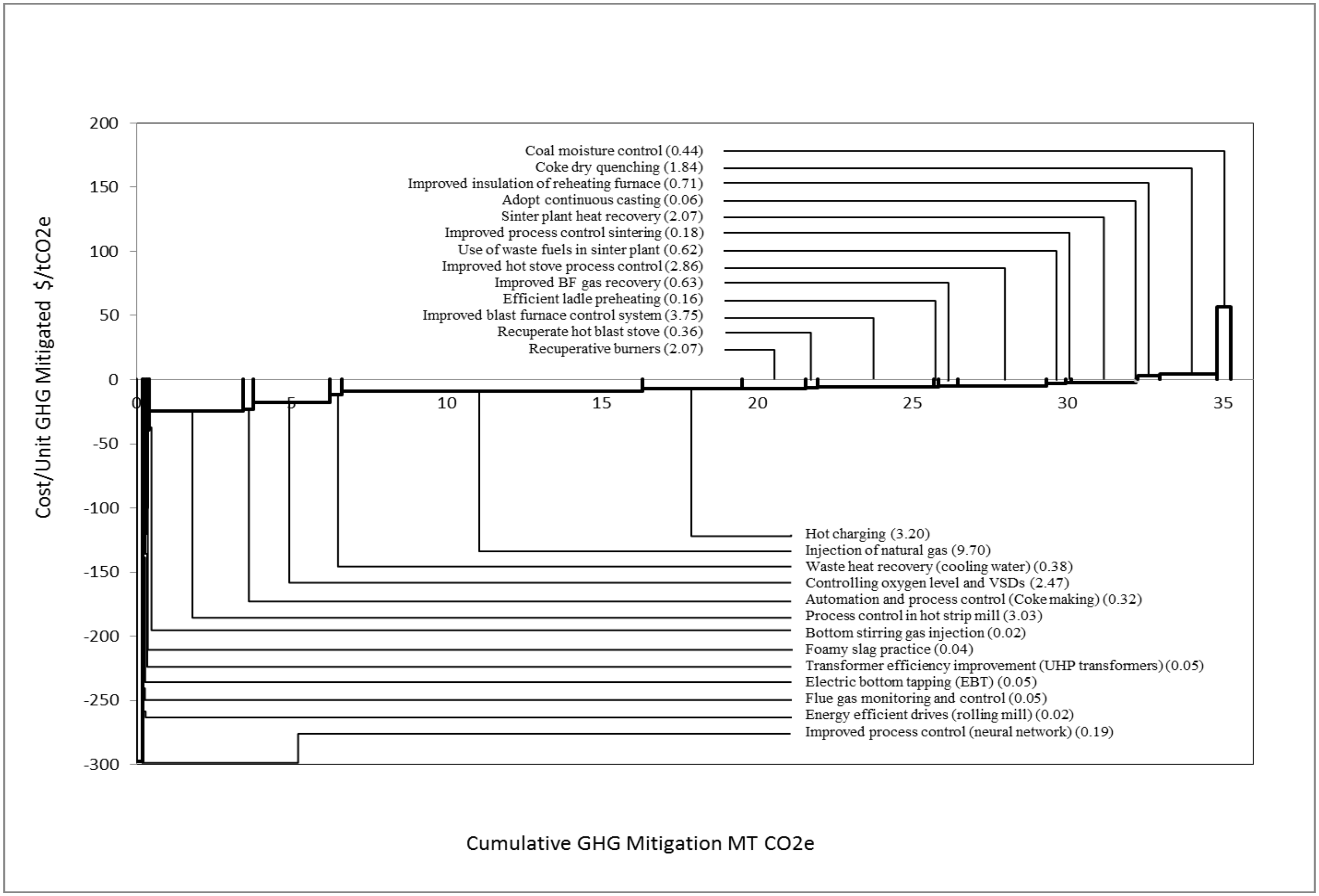

Figure 4-11: Fast penetration scenario GHG emission cost curve (2050 time horizon)

In the slow penetration scenario, the cumulative emissions reduction potential is calculated to be more than 35 million tonnes of CO_2 eq, more than 94% of which is achievable with a negative GHG abatement cost. The higher percentage of achievable emissions reduction with negative cost in the slow penetration scenario (compared to the fast penetration scenario) is mainly due to the increasing trend of the fuel prices in future years.

4.6.1. Sensitivity analysis

In order to assess the sensitivity of the results to input variables, we analyzed the impacts of fuel price and discount rate on the GHG abatement cost of different energy efficiency measures in the fast penetration scenario (i.e., 2030 time horizon). While the observations from sensitivity analysis are presented here; detailed results are presented in Appendix III-III.

In the analysis, we used nominal discount rate of 5% (Section 4.5.1). In order to assess the sensitivity of the results to this assumption, we also considered discount rates of 4% and 6% (i.e., ±20% of the initial assumption). The results show that impacts of ±20% change in the discount rate will result in changes in the GHG abatement cost in the range of ±15%. We found that changes in the discount rate will not impact the relative economic performance of different energy efficiency measures (i.e., the relative position of different GHG mitigation measures in the cost curve). In addition, we observed that regardless of the considered discount rate, more than 90% of the emissions reduction is achievable with negative GHG abatement cost.

In order to assess the sensitivity of the results to the price of fuel, we used different projections by the National Energy Board [282]. More specifically, while the reference fuel price projections was used for scenario analysis, in the sensitivity analysis we also applied the low and high fuel price scenarios as shown in Table 4-9.

Table 4-9: End-use industrial fuel price (CAD/GJ)[282]

Fuel price scenario	Fuel price	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low fuel price	Natural gas	4.38	3.90	2.63	3.91	3.56	3.56	3.56	3.58	3.61	3.63	3.64	3.70	3.83	3.96	4.06	4.16	4.27	4.36	4.45	4.54	4.61
	Coke	1.50	1.52	1.55	1.57	1.59	1.62	1.62	1.65	1.67	1.70	1.72	1.75	1.78	1.80	1.83	1.86	1.88	1.91	1.94	1.97	2.00
	Electricity	17.60	19.78	21.25	22.32	22.27	21.97	21.80	21.85	21.88	21.68	21.64	21.61	21.57	21.66	21.72	21.73	21.99	22.37	22.86	22.91	23.21
Reference fuel price	Natural gas	4.38	3.90	2.63	4.00	4.10	4.19	4.29	4.47	4.63	4.80	4.97	5.13	5.24	5.35	5.44	5.54	5.63	5.72	5.80	5.88	5.95
	Coke	1.50	1.52	1.55	1.57	1.59	1.62	1.64	1.66	1.69	1.72	1.74	1.77	1.79	1.82	1.85	1.88	1.90	1.93	1.96	1.99	2.02
	Electricity	17.60	19.78	21.24	22.34	22.37	22.12	22.04	22.17	22.27	22.11	22.16	22.69	22.87	23.43	23.55	23.60	24.34	24.51	24.71	24.83	25.62
High fuel price	Natural gas	4.38	3.90	2.63	4.10	4.85	5.70	5.79	5.96	6.11	6.26	6.42	6.58	6.69	6.78	6.87	6.96	7.05	7.14	7.22	7.30	7.37
	Coke	1.50	1.52	1.55	1.57	1.59	1.62	1.66	1.68	1.71	1.73	1.76	1.78	1.81	1.84	1.87	1.89	1.92	1.95	1.98	2.01	2.04
	Electricity	7.60	19.78	21.24	22.35	22.39	22.38	22.49	22.73	22.94	22.82	23.73	24.77	25.03	25.31	26.18	26.42	26.49	26.81	27.13	28.16	29.11

The impacts of fuel price on the economic performance of mitigation options vary among different measures. More specifically, changes in the GHG abatement cost were minimal (i.e., less than 1%) for use of waste fuels in sinter plant, efficient ladle preheating, sinter plant heat recovery, improved process control-sintering. For measures such as waste heat recovery (cooling water), improved insulation of reheating furnace, hot charging, coke dry quenching, the impact of fuel price on the GHG abatement cost is considerable. For the first category of technologies (with minimal impact of fuel price on the GHG abatement cost), the main energy saving is in form of reduction in coke consumption. As shown in Table 4-9, the difference in the price of coke is minimal among different fuel price scenarios and that results in a negligible fluctuation in the GHG abatement cost when considering different fuel price scenarios. For the second group of technologies, the share of fuel price in total cost of the technology (i.e., capital cost, O&M cost and fuel cost) is relatively high and therefore the changes in the fuel price have resulted in considerable changes in the GHG abatement cost. Overall, we found that changes in the fuel price will neither impact the relative positioning of different measures in the GHG abatement cost curve nor they will change the amount of GHG emissions which is achievable with negative cost.

4.7. Conclusion

In Canadian industries, the iron and steel sector accounts for 6% and more than 8% of overall energy consumption and GHG emissions, respectively. The continuation of historical trends is expected to result in an increase of 25% in the industrial sector's overall GHG emissions by 2030. This makes the iron and steel sector accountable for 12% of industrial GHG emissions. Considering the ambitious government targets for GHG mitigation, emissions reduction from industry is critical. In order to assess the GHG emissions reduction potential in the industrial sector, scenario analysis was applied to assess long-term energy efficiency improvement and GHG mitigation potential. An analysis of the results of the BAU scenario suggests that structural change in industry (i.e., increasing shares of EAFs rather than the integrated route) will lead to more than 11% improvement in the energy of the iron and steel industry.

26 mitigation scenarios were developed over the time horizons of 2030 and 2050. In order to assess the economic performance of each, the cost of saved energy and GHG abatement cost were calculated. The results suggest that if energy efficiency options are implemented, more than 17 and 35 million tonnes of CO_2 eq emissions reduction are achievable in the fast and slow penetration scenarios, respectively. This translates to approximately 5% reduction in annual emissions compared to the baseline scenario. In both scenarios, more than 90% of the achievable emissions reduction is achievable with negative costs.

Overall, the results of the analysis suggest that the biggest factor affecting GHG emissions in the sector are structural change (i.e., the EAF versus the currently dominant EAF route). In addition, the implementation of energy efficiency options results in an average 5% reduction in GHG emissions from the industry. The negative cost of emissions reduction is expected to improve the economic competitiveness of the Canadian iron and steel industry.

Chapter 5 : Assessment of the impacts of process-level energy efficiency improvement on greenhouse gas mitigation potential in the petroleum refining sector[13]

5.1. Introduction

The industrial sector is responsible for more than 30% of global greenhouse gas (GHG) emissions [326, 327]. Within the sector, the oil and gas industry accounts for 39% and 37% of the energy consumption and GHG emissions, respectively [328]. In petroleum refining industry, fossil fuels are used as both feedstock and a source of process energy. In addition to its environmental footprint, energy makes up almost 50% of the operating cost in petroleum refining industry [329]. Therefore, energy efficiency improvement in the refining sector offers not only potential for GHG mitigation but also significant potential for cost savings [330, 331]. This becomes more important when considering the economic impacts of environmental regulations and GHG mitigation targets on the profitability of petroleum refining industry [332].

A detailed literature review found that there is limited research which focuses on integrated analysis of process-level energy efficiency improvement and its impact on systems-level GHG mitigation potential. In other words, despite the crucial importance of fact-based climate change policy making, the existing literature either solely focusses on efficiency improvement in a specific process (without much focus on its impact at the systems level) or conducts high-level system analysis (without comprehensively assessing the technical feasibility of the energy efficiency options). This is a key gap.

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[13] A version of this chapter is submitted Journal of Cleaner Production as Talaei A, Oni A, Ahiduzzaman Md, Roychaudhuri P, Rutherford J, Kumar A. “Assessment of the impacts of process-level energy efficiency improvement on greenhouse gas mitigation potential in the petroleum refining sector”, 2019 (submitted)

Most studies assess the technological and economic performances of a single measure. For example, Tahouni et al. assessed the impact of flare gas recovery networks on energy in a petroleum refining plant [20]. Other studies assessed the technological performance of measures such as the effectiveness of the fuel gas network on reducing the flaring [21], the feasibility of thermal coupling between the crude distillation unit and the delayed coking unit [22], and the impacts of the integrated heat exchanger network on the energy consumption in the crude distillation unit (CDU) [333]. In addition to energy saving potential, the economic performance of energy efficiency measures was analyzed in several studies. For instance, studies assess waste heat recovery potential and the economic implications in different petroleum refining sub-units [29], the application of the recovered waste heat for thermal desalination and electricity generation [30], and the effect and economic effectiveness of visbreakers on NO_2 [31]. In a study by Liu et al., a new absorption-stabilization process in gasoline and liquid petroleum gas (LPG) production was proposed and it was found that the new two-stage condensation section has the potential to reduce cold and hot utility demand (by 18% and 26%, respectively) with a payback period of 17 months [334].

Few studies apply systems-level approaches to analyze energy efficiency in the petroleum refining sector. Studies in this category either focus on analyzing the energy efficiency potential in a refining complex or in the refining sector as a whole. For example, in the study by Holmgren and Sternhufvud, the short-term potential for energy efficiency improvement and CO_2 mitigation were analyzed in several Swedish refineries [335]. When considering the sectoral analysis, earlier studies conducted under the Environmental Protection Agency and International Energy Agency GHG Programs provide a comprehensive list of energy efficiency measures and their technology readiness level (TRL) [336]. Despite the inclusiveness of the above-mentioned studies in terms of technology operation, data on potential efficiency improvement and the technology cost are missing for most of the technologies assessed. Worrel and Galitsky identified energy efficiency opportunities in the US petroleum refining sector. They presented a comprehensive list of energy efficiency measures based on findings from the literature and real-world projects and analyzed the economic performance (i.e., payback period) for some of the opportunities. They suggested further analysis on the applicability and economic performance of the measures [337].

Overall, a review of the literature suggests that there is an obvious gap in systems-level analysis of long-term GHG mitigation potential from the refining sector. In addition, while there are several technical and engineering analyses of energy efficiency in the refining sector, we found that there is minimal data on the economic performance of these technologies. These limitations impose uncertainties not only in the cost of emission reduction but also in the adoption rate of efficiency technologies, which is highly affected by the economic attractiveness of the energy efficiency technologies.

A system-level quantitative assessment of energy efficiency improvement and GHG mitigation potential from the sector are crucial for both climate mitigation policy making and industrial investment. More specifically, an overall estimate of the achievable GHG emissions reduction from the sector provides the ground for policy makers to assign sectoral GHG emissions budgets while developing long-term national and regional emissions reduction strategies. Moreover, considering the increasing number of environmental regulations and in order for industries to remain competitive in a carbon-constrained world, it is important for industrial stakeholders to understand the available GHG mitigation options, their role in helping industry respond to the requirements of environmental standards, and the cost/benefits associated with implementing the energy efficiency and GHG mitigation options it.

The main objective of the current study is address research gaps by developing a framework that integrates process modelling, long-term integrated resource planning, and techno-economic analysis to assess the long-term energy efficiency improvement and GHG mitigation potential in the refining sector and the long-term economic performance of the identified energy efficiency measures. The specific objectives are to:

- Identify the major energy-consuming sub-sectors in the refining industry;
- Determine process improvement options, their costs, and energy saving potential through process modeling;
- Assess the long-term GHG emissions mitigation potential and abetement cost for each process improvement option; and
- Analyze the applicability of the framework for long-term climate change policy making.

The contribution of the current research is two-fold. First, a comprehensive data-intensive framework that includes process simulation, energy planning, and economic models is developed. Different types of refining processes (conventional and non-conventional oil refining processes) are modeled, making the model flexible and the study the GHG mitigation potential in other juristications possible. Second, to the best of the authors' knowledge, the reseach in this Chapter is the first study that analyzes the long-term GHG mitigation potential in the Canadian petroleum refining sector.

The Chapter is structured as follows: Section 5.2 describes the method used to develop the framework and Section 5.3 gives the details of the application of this framework in a case study of the refining sector in Alberta. The results of the case study are presented in Section 5.4, and applicability of the resutlts for long-term policy making is presented in Section 5.5. Section **Error! Reference source not found.** is the conclusion.

5.2. Framework development

A comprehensive and data-intensive model was developed in Long range Energy Alternative Planning (LEAP) model to assess the status and performance of the petroleum refining industry. In addition, a simulation model was developed in Aspen HYSYS to simulate processes and analyze the technical and economic performance of various energy efficiency options in the major energy-consuming processes. The simulation results were integrated with the LEAP model to develop long-term GHG mitigation scenarios. In addition, models were developed to analyze the long-term economic performance of different energy efficiency measures and develop carbon abatement cost curve.

5.2.1. Modelling tools

5.2.1.1. LEAP model

The LEAP model is a long-term scenario analysis and energy planning framework [302]. The model uses a bottom-up approach in which technology-level energy consumption is aggregated to analyze overall energy demand in the system. The scenarios developed in the LEAP model are used to assess and forecast the growth of sectoral energy demand, energy transformation, and the distribution sectors and ultimately the demand for different types of primary energy [32, 35]. In addition, the LEAP model has a built-in Technological and Environmental Database (TED), where detailed environmental impacts of different processes and fuel combustion are available [79]. Like the other modules in LEAP, the TED can be modified based on the specific characteristics of a process. For instance, the emission factors for energy consumption could be changed depending on the specific process characteristics or the specifications of the consumed fuel. Further details on LEAP model are given in section 5.3.1.

5.2.1.2. Aspen HYSYS model

Simulation models such as Aspen HYSYS are used as a substitute for real processes [338, 339]. As it may be too expensive to experiment on pilot plants or real processes, process engineers study the process using process simulation models. Aspen HYSYS is a process modelling tool that can replicate real life refining processes. Its capabilities cover a wide range of petroleum refining processes. Aspen HYSYS has been widely used to refine process analysis, identify alternatives that improve systems and reduce costs [340, 341], and investigate the impact of increasing throughput [342].

5.2.1.3. Integrated modeling framework

An integrated framework was developed to unify Aspen HYSYS and LEAP models as shown in Figure 5-1. The initial sets of input data (both process- and system-level) were acquired through comprehensive literature review and consultation with industrial stakeholders. Wherever data was not available, it was developed based on fundamental engineering principles. These data were used to populate the LEAP model and the Aspen HYSYS model. The two models were then set to interact dynamically. More specifically, in each step of simulation, the outputs from one model were used as inputs or validation indices for the other model. The techno-economic performance of different energy saving measures (the results of the process simulation model) is used to develop GHG mitigation scenarios in the LEAP model. The technologies' long-term performance at the system level together with the macroeconomic data such as fuel price, inflation, and discount rates are then used in the techno-economic model to assess the long-term economic performance of different scenarios. The step-wise modeling procedure is shown in Figure 5-1 and described in sections 5.2.2 to 5.2.4.

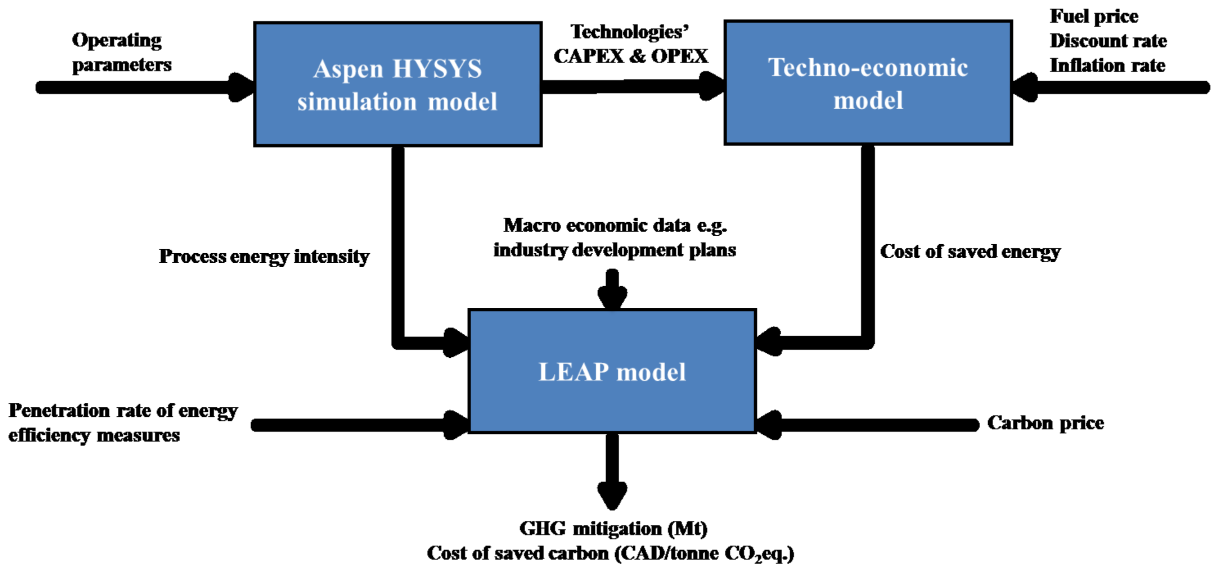

Figure 5-1: Method for GHG mitigation cost curve development

5.2.2. System analysis

System analysis in this study involves investigating the production process, identifying the major energy-consuming sub-processes, and developing an energy demand tree. To develop an energy demand tree for the petroleum refining industry, the energy intensity (i.e., energy consumed per unit of input feedstock) of the major energy-consuming processes needs to be analyzed. The process-level energy intensities are used to develop the base year database in the LEAP model. In the model, the plant's operational capacity and the capacity factor of each sub-process together with process-level energy intensity and emission factors are used to calculate the industry-level energy consumption and GHG emissions. These data are verified against the industrial-level aggregated data available through governmental datasets.

5.2.3. Scenario analysis

The first step in scenario analysis is to define the base year. The year 2010 is considered the base year in order to ensure the availability and consistency of various data used in the analysis. More updated data were used where available. In order to assess future energy saving and GHG mitigation potential, a baseline scenario (also referred to as the reference or business-as-usual [BAU] scenario) and several GHG mitigation scenarios were developed.

In order to assess the impacts of gradual and holistic energy efficiency improvements on the sectoral GHG mitigation potential, two time horizons (the first from 2010 to 2030 and the second from 2010 to 2050) were used to develop the fast and slow penetration scenarios for each energy efficiency option. It is assumed that the full penetration of the energy saving measures would be realized by the end of each time horizon. That is, for the fast and slow penetration scenarios (i.e., 2030 and 2050 time horizons, respectively), it is considered that the full potential for energy-efficient technology diffusion would be realized by the end of 2030 and 2050, respectively.

5.2.4. Economic analysis

The cost of saved energy (CSE) and the GHG mitigation cost were calculated and used as indicators to analyze economic performance in different energy efficiency options. The CSE is defined in detail later in this section. The CSE and the GHG mitigation cost were calculated through development of techno-economic models and in the LEAP model, respectively. In addition to macroeconomic factors such as discount rate, inflation rate, fuel price, and carbon price, several technology-level characteristics (e.g., capital cost and O&M cost) of different energy efficiency options were considered.

5.2.4.1. *Cost of saved energy*

The cost of saved energy (CSE) is defined as the cost associated with mitigating one unit of energy consumption (i.e., CAD/GJ) and is used as an exogenous parameter in the LEAP model. The CSE is an index for assessing the economic feasibility of an energy efficiency investment and is defined as shown in Equation 5-1 [79].

$$CSE = \frac{\sum(C_{EE} - C_{Base}) + \sum(O\&M_{EE} - O\&M_{Base}) + \sum(F_{EE} - F_{Base})}{\sum EC_{Base} - EC_{EE}}$$ **Equation 5-1**

In Equation 5-1, annualized capital cost (C), operation and maintenance cost (O&M), and fuel cost (F) are considered for both the existing technology (base) and the energy-efficient technology (EE). National Energy Board projections, a federal agency in Canada, were used for the reference scenario fuel price for the years 2015-2035 [282]; these data were extrapolated to forecast fuel price after 2035.

All the costs were annualized, and the difference in the total costs for energy-efficient and base technologies was used as the numerator in the equation. The denominator is the difference between the energy consumption of the energy-efficient and the base technologies. A nominal discount rate of 5% and an inflation rate of 2% were used to account for the time value of the investment and expenses. In addition, the lifetime of each technology was considered [282].

5.2.4.2. *GHG abatement cost*

The GHG abatement cost is defined as the incremental cost associated with reducing one tonne of greenhouse gas emissions (i.e., equivalent CO_2 emissions) with respect to the baseline. The net present value (NPV) is used as the economic indicator for calculating the incremental GHG mitigation cost (CAD/tonne of CO_2). The NPV is an economic index that presents the value of the investment using the future cash flow (revenues minus expenses) and the discount rate and is calculated as shown in Equation 5-2:

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i} \qquad \textbf{Equation 5-2}$$

In Equation 5-2, "i" is the year, "n" is the time period of the study, "CF_i" is the net cash flow in year "i" compared to the baseline, and "r" is the discount rate. The NPV of different options is directly calculated through the LEAP model. The GHG mitigation cost is calculated using the cumulative GHG emissions reduction and NPV of each option.

5.2.4.3. The development of GHG abatement cost curves

Incremental GHG abatement cost curves were developed to assess the costs and benefits of various mitigation scenarios. Cost curves show the estimated incremental abatement costs to avoid a tonne of GHGs (CAD/tonne of CO_2 mitigated).

5.3. Framework application: Case study for Alberta

To demonstrate the effectivenss of the proposed framework, a case study was conducted for Alberta, a western province in Canada. With a crude distillation capacity of 1.98 million barrels per day (0.31 million cubic meter per day), Canada hosted more than 2% of the global petroleum refining capacity in 2015 [343]. In Canada, the 10^{th} biggest oil refining country in the world [344], the petroleum refining industry made up 9.5% of the country's GHG emissions in 2014 [345]. Almost 25% of Canada's refining capacity is located in Alberta, which makes the province home to the largest refining capacity in the country [346].

Considering the anticipated increasing trend in GHG emissions from the petroleum refining sector [65] (i.e., as a result of capacity expansion plans [347]) and Alberta's ambitious targets for emissions reduction and energy efficiency improvement [208], it is crucial to understand the energy efficiency improvement and GHG emissions mitigation potential in the petroleum refining sector.

5.3.1. Alberta LEAP model

We developed a detailed LEAP model for the Canada [61]. In order to assess the interactions between different energy system subsectors, a data-intensive model, covering all stages of the energy system (i.e., resources, transformation [301], and demand side including residential [62], commercial [63], cement [79], and chemical industries [80] etc.), was also developed (Figure 5-2) [301]. The model (including both supply and demand sectors) was used to insure that the interactions between various modules in the energy system are accounted for [61]. The following sections focus on the petroleum refining industry in the demand side only.

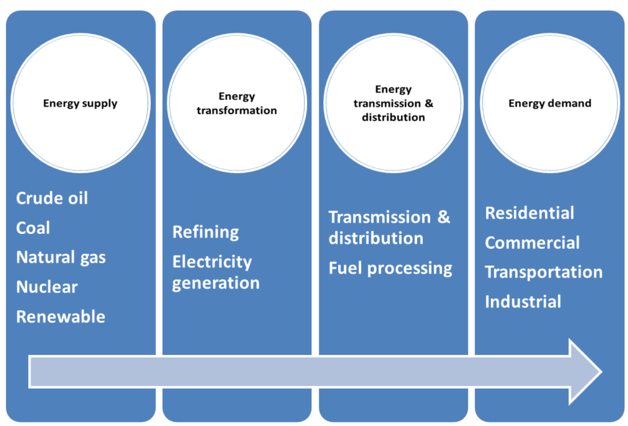

Figure 5-2: Structure of energy system in the LEAP model

5.3.2. Energy consumption in the refining process

The starting point in the analysis is to identify the major energy-consuming processes in the petroleum refining sector. The typical refining operations are classified into three categories: separation, conversion, and treatment [348]. Each of these operations includes several sub-processes with specific pressure and temperature as working conditions. In general, the sub-processes of the main section in a refinery are:

- Separation: desalting and distillation (vacuum and atmospheric distillation).
- Conversion: cracking, alkylation and reforming
- Treatment: hydro-treating and blending

5.3.2.1. Energy consumption demand tree

The operating loads of different unit processes combined with their energy intensity are determining factors in the total energy consumption of each unit process. In terms of energy consumption, petroleum refining uses energy in the form of fuel, steam, and electricity. Energy is consumed to heat crude units and feed streams or to produce steam for powering mechanical devices [349]. Because petroleum refining is a multi-product industry, it is difficult to allocate the energy consumption and GHG emissions to specific refinery products [350]. That said, furnaces, boilers, and utilities are known to be the main energy consumers in a typical petroleum refinery [351] .

Specific energy consumption (SEC) in refineries is affected by different factors such as crude quality, refinery complexity, product type, and the shares of final products [352, 353]. Generally, heavier feedstocks need more energy per unit of refined product [354]. In Alberta, specific energy consumption in oil sands refineries is reported to be almost 17% higher than in refineries using conventional oil as feedstock. The breakdown of energy consumption in different refining subsectors of conventional and oil sands refineries is shown in

Table 5-1.

Table 5-1: Energy intensities in different refinery sub-processes[14,15]

PROCESS	CONVENTIONAL			OIL SANDS REFINERY			FUEL TYPE
	Steam	Fuel	Electricity	Steam	Fuel	Electricity	
	GJ/m³	MMBtu/m³	kWh/m³	GJ/m³	MMBtu/m³	kWh/m³	
Desalting[16]	0.00	0.00	0.31	-	-	-	Electricity, steam, still gas[17]
Crude distillation	0.27	0.46	4.28	0.27	0.33	3.96	Electricity, steam, still gas
Vacuum distillation	0.33	0.33	2.20	-0.20	0.33	3.33	Electricity, steam, still gas
Alkylation	2.19	0.00	45.29	4.11	0.00	8.55	Electricity, steam
Coking	-0.07	0.80	39.00	0.13	0.86	32.96	Electricity, steam, fuel oil, still gas,
Fluid catalytic cracking	0.00	0.40	23.40	-0.93	0.33	2.45	Electricity, steam, fuel oil, still gas
Hydrocracking	0.46	0.93	70.45	0.60	0.53	64.03	Electricity, steam, still gas
Catalytic reforming	0.60	1.19	18.43	-0.66	1.59	4.15	Electricity, steam, natural gas
Isomerization	1.33	0.00	12.27	4.65	0.00	5.72	Electricity, steam
Hydro-treating	0.46	0.46	26.42	0.20	0.53	12.89	Electricity, steam, still gas

In addition to energy intensity, the operating load of a specific sub-unit in the petroleum refinery is a determining factor in energy consumption in different unit processes.

Table 5-2 shows the typical operating load of each unit process as a percentage of the refinery load (i.e., total crude oil entering the process unit/operating load of the crude distillation unit).

[14] The negative figures indicate that the process is a net energy producer.
[15] Due to the non-disclosure agreement between the Industrial Research Chair Program and the industrial stakeholders, the sources for industrial data are not cited here.
[16] Generally, oil sands refineries do not have a desalting unit as desalting is usually done during the upgrading process.
[17] Synonymous with refinery gas or fuel gas

Table 5-2: Typical distribution of the different refining processes [348]

Unit process	Distribution (share of CDU capacity (%))	
	Oil sands refinery	Conventional refinery
Crude distillation	100.0	100.0
Vacuum distillation	33.9	41.6
Thermal processes (delayed coking, thermal cracking, visbreaking)	11.3	14.6
Fluid catalytic cracking	25.2	32.5
Catalytic reforming	6.3	19.3
Hydrocracking	14.2	10.0
Hydrotreating	94.2	87.9
C_4 alkylation	7.9	6.6
Isomerization	4.5	3.7

The energy intensity of different processes was combined with the type of energy carrier used in each process to develop the energy consumption demand tree. It needs to be noted that this analysis does not include oil sands upgrading and mining processes; it focuses solely on the refining process. The petroleum refinery energy demand tree is developed as shown in Figure 5-3 and is used to analyze energy consumption in different process units.

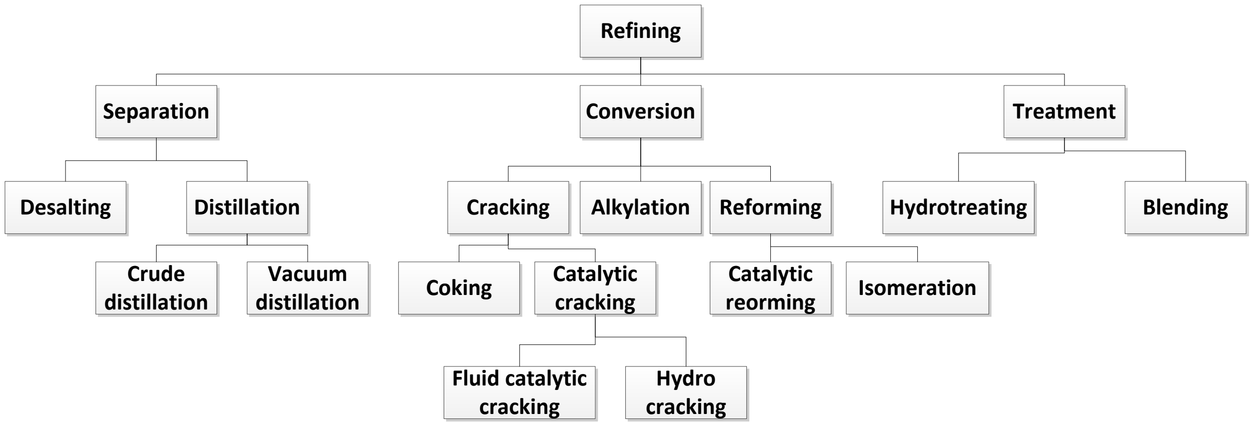

Figure 5-3: Petroleum refinery energy consumption demand tree

5.3.2.2. Model verification

The demand tree was used to populate the LEAP model database. The database was then validated with publicly available data and the developed process simulation models. That is, the production capacity of each refinery in Alberta and the specific energy consumption data at the technology- and process-level used to populate the LEAP model database were aggregated to calculate the energy consumption of Alberta's petroleum refining industry. The data were then compared to the cumulative industry-level actual energy consumption data from Natural Resources Canada (NRCan) for the years 2000-2013 [355].

For model verification, it is important to distinguish between petroleum refining capacity and the actual run-to-stills. In other words, petroleum refinery use rates fluctuate depending on the availability of the refining unit and the demand for products. Also, for safety reasons, the actual capacity of a refinery is usually larger than the nominal capacity, and therefore the refinery could operate above its nominal capacity. As shown in Figure 5-4, despite historical under-utilization of the refineries in Alberta, in recent years refinery use rate has hovered around full capacity. The refinery use rate in Alberta, moreover, is higher than the national average. While the national average has fluctuated between 78% and 95% since 2000, in Alberta the rate has been almost constant and slightly less than 100% [356].

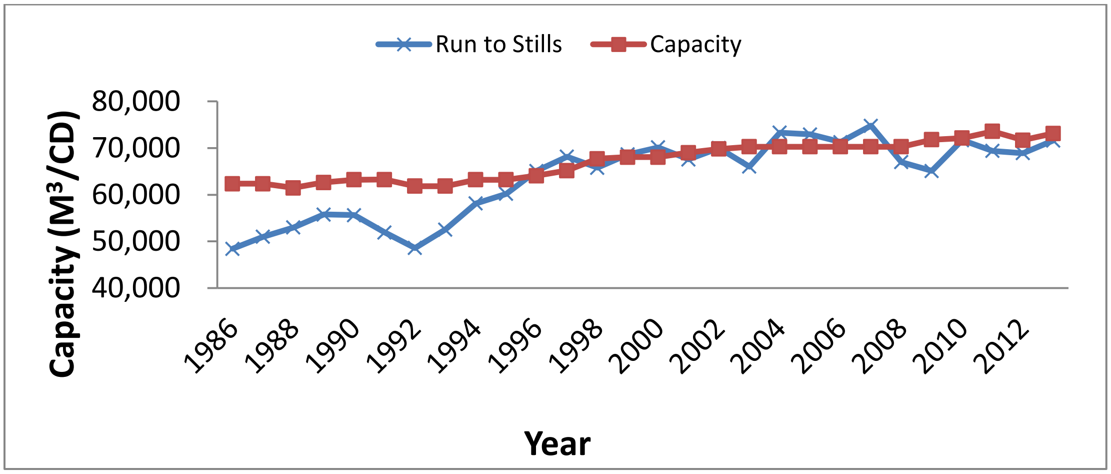

Figure 5-4: Production capacity vs run-to-stills production in Alberta

The historical energy intensity of refining sub-processes together with the run-to-stills capacity of each refinery were used to calculate Alberta's refining sector energy consumption and GHG emissions. The results are shown in Figure 5-5 and Figure 5-6.

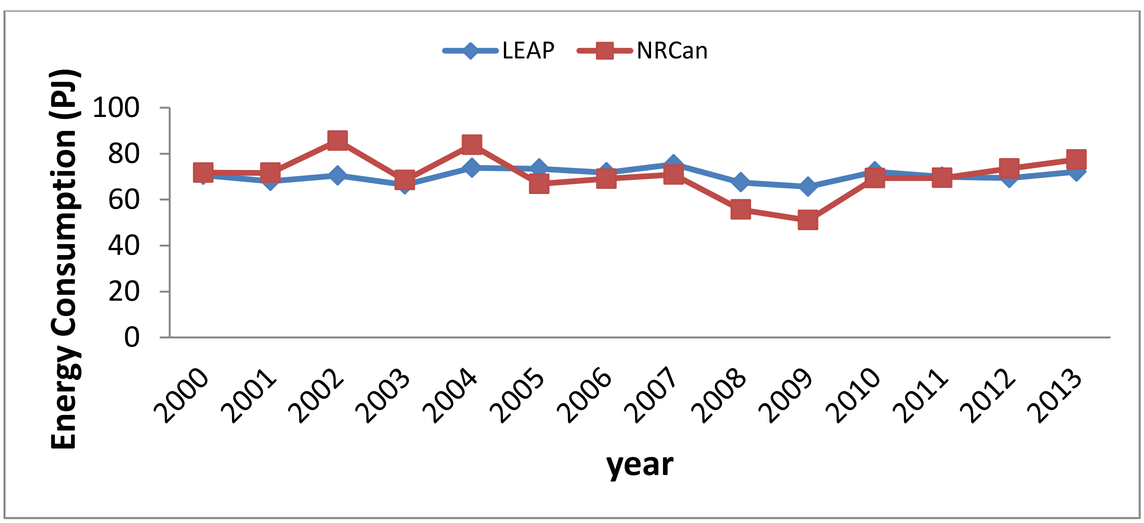

Figure 5-5: Overall energy consumption in Alberta's refining sector

As shown in Figure 5-5, the results of the LEAP model developed for total energy consumption are consistent with the data reported in Natural Resources Canada's Comprehensive Energy Use Database [234]. The model effectively captured the energy consumption peaks in 2002 and 2004 as well as the sudden decline in energy consumption in 2008 and 2009.

Except for 3 years (2002, 2004, and 2009), the results of the LEAP model are within 10% of actual energy consumption data. Although the actual production of the refineries and the energy intensities of different sub-processes are the main factors affecting the energy consumption in a refinery (i.e., process-specific energy consumption), energy is used in other subsectors where it is not directly proportional to the use rate. For example, a certain amount of lighting and cooling and heating water, etc., is needed for a refinery complex to run regardless of its operation conditions; the use of this type of energy is considered to be beyond the scope of the current work.

For natural gas and different oil products, the International Panel on Climate Change's (Tier 1) default emission factors available in the Technology Emission Database of LEAP were used [357]. For still gas, petroleum coke, and fuel oil, emissions data were taken from the US Environmental Protection Agency (EPA) [358]. The GHG emissions from the sector were calculated, and the results are presented in Figure 5-6.

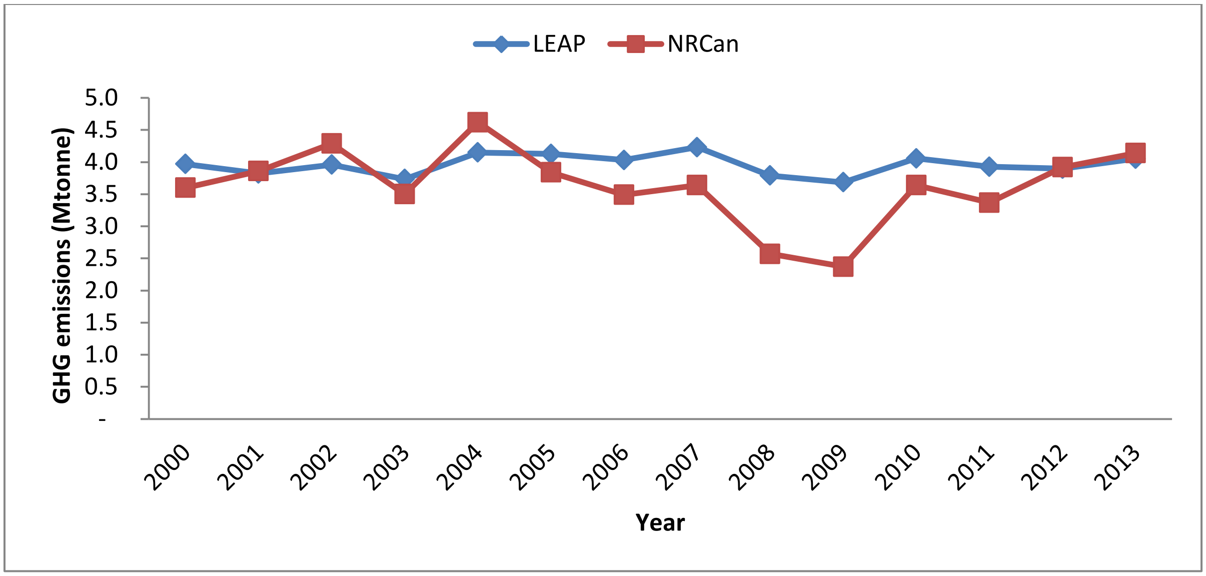

Figure 5-6: GHG emissions from Alberta's refining sector

5.3.3. Scenario analysis

5.3.3.1. Baseline scenario

The baseline scenario was developed both as the base for comparison and to represent the most probable pathway for petroleum refining sector development in Alberta. To develop both baseline and mitigation scenarios, it is essential to predict future development in the sector. The continuation of historical capacity expansion together with confirmed governmental plans for new refineries were considered to forecast future sectoral capacity. No refineries have been built in Alberta since the 1970s [359]. However, since the 1950s, refining capacity has increased steadily, and it stabilized after 2000 [359] (Figure 5-7). The simultaneous increase in refining capacity and decline in the number of refineries over time highlights the fact that the complexity of the refining sector in Alberta is increasing. In other words, rather than building new refineries, industry has focused on increasing the capacity of existing plants (by adding complex process units) where the demand for final refining products could be met more economically.

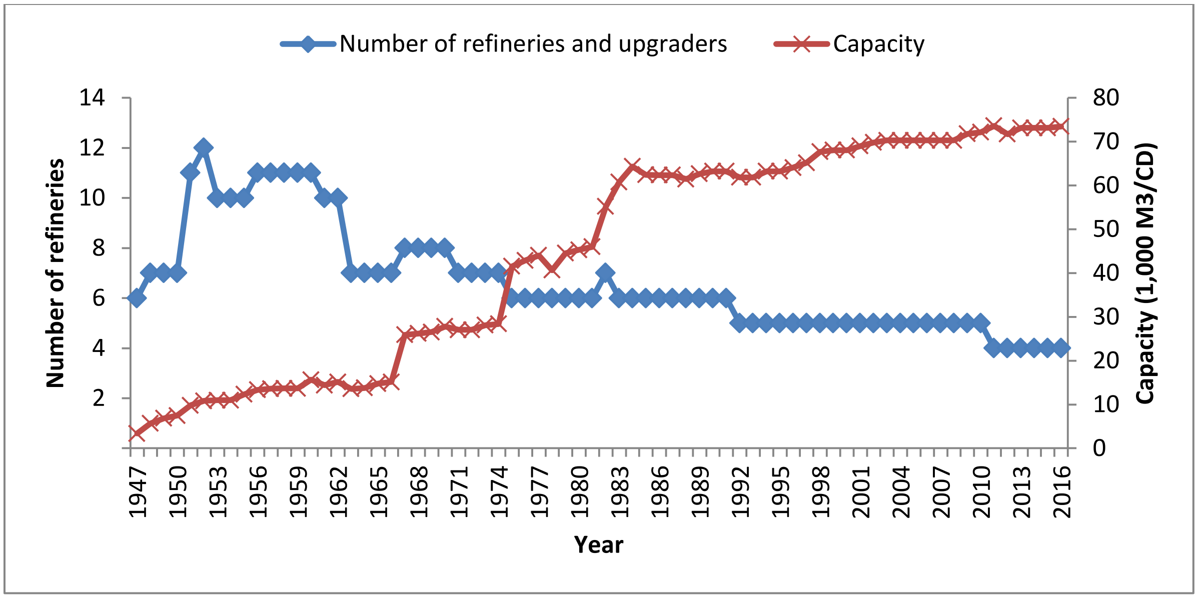

Figure 5-7: Petroleum refining capacity in Alberta [359]

The Sturgeon Refinery's capacity expansion plans were considered in developing the baseline scenario. The first phase of the Sturgeon Refinery plant became operational in 2017 and full capacity of 7,949[18] m^3/day is expected by 2022 [360-363]. Figure 5-8 shows the long-term capacity projection that is used for scenario analysis.

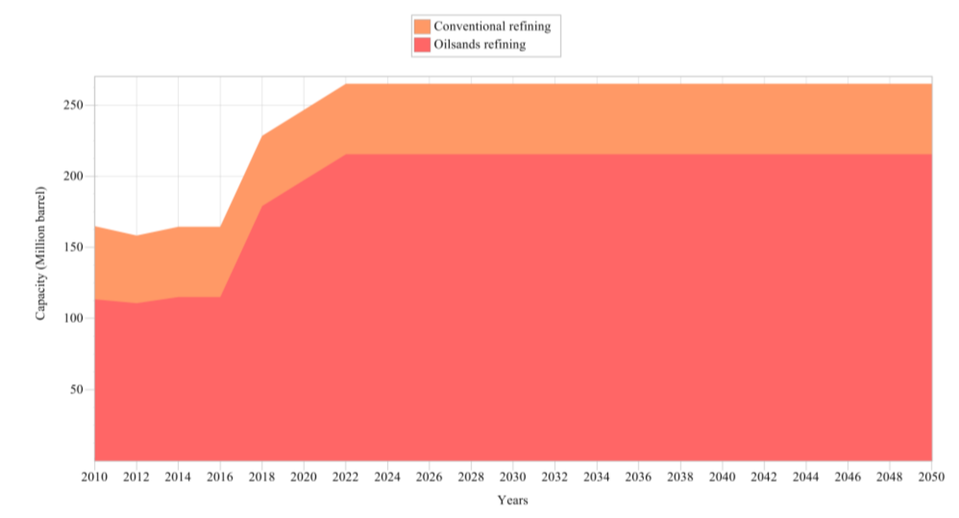

Figure 5-8: Long-term capacity of the refining sector in Alberta

[18] The following conversing factor can be used to convert cubic meters to barrels of oil: $1 m^3$=6.29 bbl

In terms of technology performance, it is considered that in the baseline scenario there would not be any major changes in the energy intensity of the processes. In other words, the baseline scenario is the case where no major actions take place for energy efficiency improvement.

5.3.3.2. Alternative scenarios

As discussed in section 5.2.3, the purpose of developing alternative scenarios is to assess the energy savings and GHG mitigation potential achievable by implementing various energy efficiency options in the system. We developed the alternative scenarios in two stages: first, we identified the energy measures and assessed their technical and economic performance through development of process simulation models in the Aspen HYSYS and second, we integrated the results in the LEAP model to forecast their long-term impact on sectoral GHG emissions.

The comprehensive literature review shows that there is energy efficiency improvement potential in almost all subsectors of the refining process. Following the review, we developed a refinery process model in Aspen HYSYS version 8.8 to simulate the existing processes for each process and analyze the impacts of implementing the efficiency option on energy consumption in the unit of interest (assumptions and process flow diagrams for different units are provided in Appendix VI-I). The capital cost associated with implementing each option was extracted from the process model and then modified in order to represent the situation in Alberta. For consistency, all the cost data were converted to the Canadian dollar (CAD) (using the exchange rate and inflation rate) for the year 2010, the base year of the current study.

The eleven energy efficiency options selected in this study were classified into four categories:

- Heat integration
- Preheating the combustion air

- Application of new technologies (i.e., heat pumps)
- Energy-efficient equipment (i.e., pumps).

These energy efficiency options are practical approaches used by various chemical and petrochemical industries to reduce the energy consumption of process plants.

To analyze each option, the following assumptions were made:

(1) The system is in a steady state flow condition

(2) Kinetic and potential energy are negligible

(3) The temperature (T_o) and pressure (P_o) at the reference state (ambient) is T_o = 25 °C = 298.15 K and P_o = 101 kPa, respectively.

(4) The efficiency of all the refinery furnaces considered is 70%.

Descriptions of the eleven options are given in Table 5-3.

Table 5-3: Energy efficiency measures

No.	Process unit	Option name	Type of EE option	Energy efficiency option
1	CDU	CDU-HI&WHR	Heat integration and waste heat recovery	Pinch analysis, an approach to saving energy by integrating process stream heat, is applied to reduce the fuel used in the furnace. Additional heat exchangers are added to increase the temperature of the feed stream to the furnace[19].
2	CDU	CDU-AP&PO	Air preheating and process optimization	The furnace duty is optimized by preheating the combustion air. We have assumed that the combustion air is preheated from 30° to 425°C using the furnace flue gas.
3	VDU	VDU-AP&PO	Air preheating and process optimization	The furnace duty is optimized by preheating the combustion air. We assumed that the combustion air is preheated from 30° to 425°C using the furnace flue gas.
4	Hydro-treating units	HTU--AP&PO	Air preheating and process optimization	The combustion air to the furnace is preheated by the furnace flue gas (exhaust gas). When the combustion air temperature increases, the furnace duty also increases. The increase in furnace duty reduces the fuel required to maintain the existing furnace duty. We assumed that the combustion air is preheated from 30° to 425°C.
5	Catalytic reforming unit	CRU-AP&PO	Heat integration	Heat recovery systems are used to preheat the feed/steam.
6	DCU	DCU-AP	Air preheating	The combustion air to the furnace is preheated by the furnace flue gas (exhaust gas). When the combustion air temperature increases, the furnace duty increases as well. This increase in furnace duty reduces the fuel required to maintain the existing furnace duty. We assumed that the combustion air is preheated from 30° to 425°C.
7	FCC	FCC-HI	Heat integration	Pinch analysis, an approach to saving energy by integrating process stream heat, is applied to reduce the fuel used in the furnace. Additional heat exchangers are added to increase the temperature of the feed stream to the furnace.
8	Hydro cracking	HC-AP	Air preheating	When the feed stream temperature increases, fuel consumption in the furnace falls. It is assumed that the combustion air is preheated from 30° to 425°C.
9	Alkylation unit	AU-HPAD	Heat pump-assisted distillation	The conventional steam reboiler unit of the distillation system is replaced by a compressor, which leads to the need for additional heat exchangers. (Note: steam is not required to reboil the bottom product; rather, the top product (distillate) is compressed with a compressor to generate heat to reboil the bottom product; electrical energy is used in this case).
10	Isomerization unit	IU-HPAD	Heat pump-assisted distillation	The conventional steam reboiler unit of the distillation system is replaced by a compressor, which leads to the need for additional heat exchangers. (Note: steam will not be required to reboil the bottom product; rather, the top product (distillate) will be compressed with a compressor to generate heat to reboil the bottom product; electrical energy will be used in this case).
11	Pumps	PUMP	Energy-efficient equipment	The installation of high-efficiency motors and adjustable speed drives (ASD) that better match speed to load requirements for motor operations reduces energy losses.

[19] An increase in the feed stream temperature reduces the amount of fuel used by the furnace

Alternative scenarios were then developed based on forecasted capacity development in the baseline scenario. For each alternative scenario, energy efficiency improvement of specific process was assessed by considering the penetration of the energy efficiency options. The interactions between efficiency options were considered and the scenarios were developed in a way that ensured they could be implemented simultaneously. In other words, the different options were modelled independently, and it was ensured that implementing one option would not impact the performance of the other options; the impact of different scenarios is therefore mutually exclusive and can be considered additive.

5.4. Results and discussion

5.4.1. Process simulation

The refinery models developed in this study are based on simplified and yet realistic assumptions. The predicted process conditions from the process simulator were compared with typical plant data. A good agreement was obtained between the simulator prediction and typical process data with an average absolute error of 6.8%. The basic input parameters for the simulation exercise and process flow diagram of each process is presented in Appendix IV-I.

The application of the improvement methods described in Table 5-4 provided energy saving alternatives for the processes. Pinch analysis is a well-known method for energy savings in a process plant's heat exchange network. We have applied the pinch method to evaluate the energy saving potential of the Crude distillation unit (CDU), Fluid catalytic cracking (FCC), and Catalytic reforming unit (CRU) units only. With the application of pinch, the percentage energy savings of the CDU, FCC, and CRU unit when compared to the base case are 1.0%, 2.38%, and 9.54%, respectively. The energy saving in each case was achieved by reducing the minimum temperature differences of the network, and splitting and adding new heat exchangers. Fuel savings in the furnaces are achieved in each process plant except the alkylation unit, isomerization unit, and the CRU. As the exiting temperature of the exhaust stream from these units is relatively high, the user needs to ensure that they do not operate above their design limits. The source of heat is exhaust gas, which leaves at an elevated temperature of 538^{o}C for each furnace considered. The percentage fuel savings varies depending on the existing operating conditions of the furnaces. As earlier mentioned, when the exhaust temperature is high, the furnace should not be operated above the design limits. Of the furnaces considered, the CDU furnace improved the most (17.2%) and the delayed coker furnace the least (2.0%). For the alkylation and isomerization units, the application of the mechanical heat pump system to its corresponding distillation unit resulted in energy savings of 7.88% and 9.33%, respectively. Lastly, the pumps are assumed to be replaced with high-efficient motors and adjustable speed drives (ASD) that better match speed to load requirements for motor operations. The application of efficient pumps resulted in percentage energy savings of about 12% compared with the base case.

The Aspen HYSYS model process simulation results in terms of the techno-economic performance of the identified energy efficiency options are shown in Table 5-4.

Table 5-4: Techno-economic performance of the energy efficiency options

	Refinery Unit	Energy savings (MJ/m^3 input)	Capital cost (2010 CAD/barrel/day)[20]	Type of fuel	Life time (years)	Penetration potential (%)
1	Crude distillation unit (CDU) – Heat integration	18.87	14.9	NG/Still gas	10	90
2	Crude distillation unit (CDU) – Combustion air preheating	56.61	27.1	NG/Still gas	10	90
3	Vacuum distillation unit (VDU)	25.16	31.4	NG/Still gas	10	90
4	Delayed coking unit (DCU)	18.87	25.5	NG/Still gas	10	90
5	Fluid catalytic cracking (FCC)	6.29	11.2	NG/Still gas	10	90
6	Alkylation unit (AU)	333.37	1866.8	Steam	10	90
7	Isomerization unit (IU)	408.85	4705.0	Steam	10	90
8	Hydrocracking unit (HCU)	75.48	154.5	NG/Still gas	10	90
9	Hydrotreating unit (HTU)	37.74	612.9	NG/Still gas	10	90
10	Catalytic reforming unit (CRU)	144.67	239.0	NG/Still gas	10	90
11	Energy efficient pumps	0.13[21]	59.3	Electricity	10	90

The process modelling results show that specific energy saving potential is highest in the Isomerization and alkylation units (409 and 333 MJ/m^3 input, respectively). However, as shown in Table 5-4, capital costs associated with energy saving from these units are also very high (1867 and 4705 CAD/barrel/day from alkylation and isomerization units, respectively). Despite the relatively limited specific energy saving potential, FCC has the lowest capital cost (i.e., 11.2 CAD/barrel/day).

[20] In order to be consistent with the common industrial units for reporting the capacity of a petroleum refining plant, we used bbl/day in this article. The following conversing factor can be used to convert a barrel of oil to cubic meters: 1m^3=6.29 bbl

[21] kWh/m^3

5.4.2. Scenario analysis

Results of the scenario analysis shows that in the baseline scenario, the energy consumption and GHG emissions from the sector will continue to increase until it reaches its maximum in 2022 (mainly as the result of capacity expansion (i.e., Sturgeon refinery)). While the impacts of integrating different energy efficiency measures on the annual energy consumption are shown in Figure 5-9 and Figure 5-10 (for fast and penetration scenarios, respectively), the cumulative impacts on the sectoral emissions reduction is presented in 5.4.4.

Total energy consumption in Alberta's refining sector is expected to reach 108.93 PJ in 2022 which will remain constant during the rest of the study period. Integration of different energy efficiency measures will result in reduction in the sector's energy consumption.

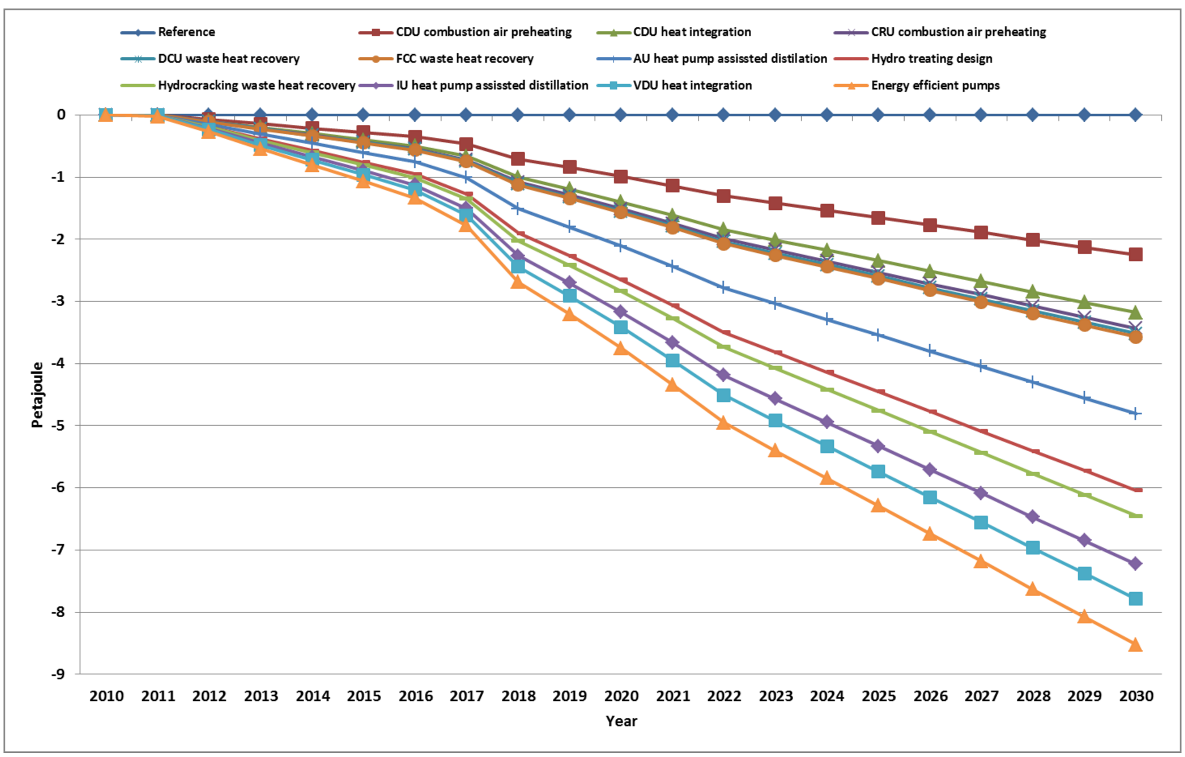

Figure 5-9: Energy saving compared to baseline scenario (fast penetration scenario, 2010-2030)

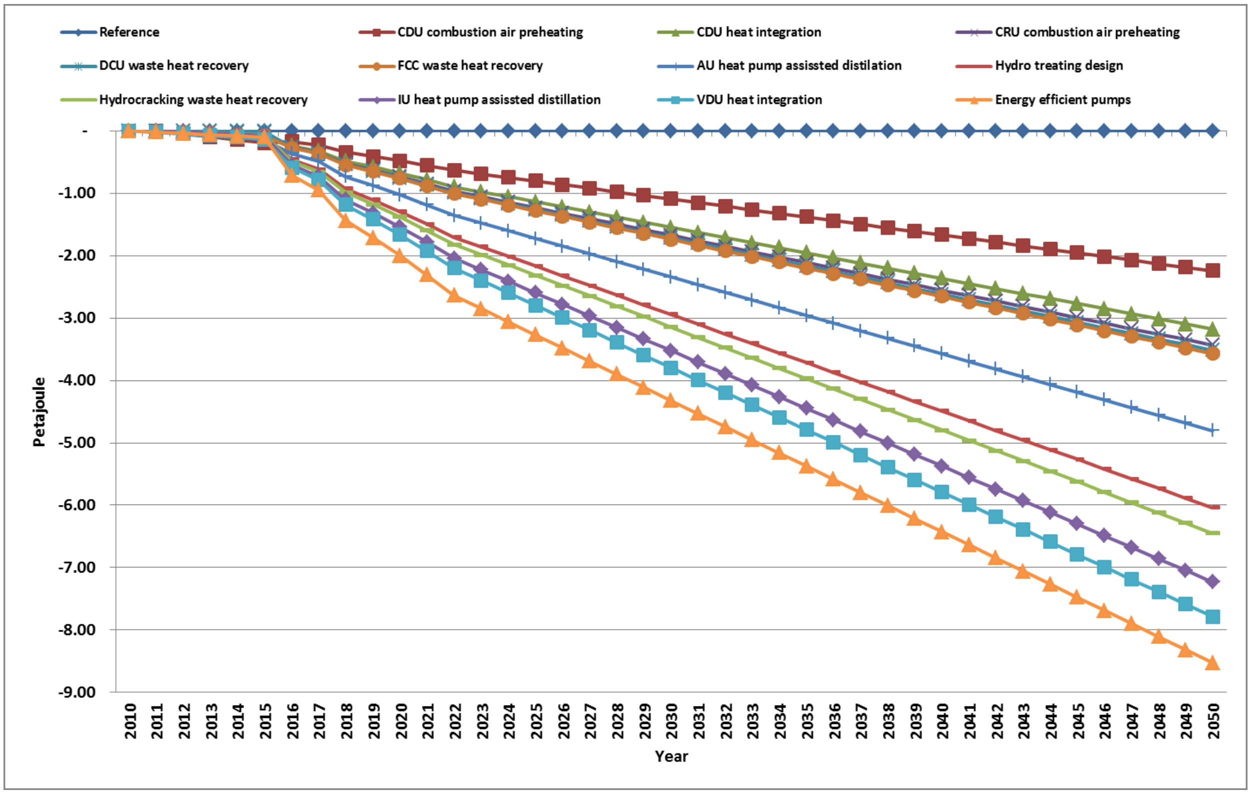

Figure 5-10: Energy saving compared to baseline scenario (fast penetration scenario, 2010-2050)

As shown, in Figure 5-9 and Figure 5-10, as a result of slow penetration rates at the beginning of time period of the study, the energy saving potential of individual measures is relatively small. On the other hand, at the end of the study period, when the full penetration potential is realized, simultaneous implementation of the energy efficiency measures will result in almost 8% reduction in energy consumption compared to the reference scenario cumulatively. As expected, air preheating and heat integration in CDU provide the biggest potential for energy saving because first, CDU has the biggest capacity factor among various refining units (

Table 5-2) and second, the energy intensity improvement of these options are relatively high compared to other options (Table 5-4). For alkylation and hydrotreating units the main factor affecting the relatively high energy saving potential is the improvement in the energy intensity rather that utilization rate of the process unit.

5.4.3. Techno-economic performance of different GHG mitigation scenarios

We evaluated the performance of each energy efficiency measure in terms of medium- to long-term energy savings, GHG mitigation potential, and associated costs. The results of both the techno-economic model (based on the developed process simulation model) and the LEAP model are presented in this section. The costs of saved energy over the time period of the study are shown for each scenario in Table 5-5. As mentioned in Section 5.2.4, in order to calculate the cost of saved energy, we considered not only the technology specific costs (e.g., capital and O&M costs) but also the cost of fuel and the time value of the money (i.e., through using inflation and discount rates).

Table 5-5: Cost of saved energy (CAD)

Scenario No.	Scenario name	2010-20	2020-2030	2030-2040	2040-2050
Scenario 1:	Crude distillation unit (CDU) – Heat integration	1.5	2.8	3.7	4.8
Scenario 2:	Crude distillation unit (CDU) – Combustion air preheating	2.2	3.5	4.4	5.5
Scenario 3:	Vacuum distillation unit (VDU)	0.4	1.7	2.6	3.8
Scenario 4:	Delayed coking unit (DCU)	0.2	1.5	2.4	3.5
Scenario 5:	Fluid catalytic cracking (FCC)	-0.8	0.5	1.4	2.6
Scenario 6:	Alkylation unit (AU)	-6.1	-4.8	-3.9	-2.8
Scenario 7:	Isomerization unit (IU)	-16.0	-14.7	-13.8	-12.7
Scenario 8:	Hydrocracking unit (HCU)	-1.3	0.0	0.9	2.0
Scenario 9:	Hydrotreating unit (HTU)	-33.0	-31.7	-30.8	-29.7
Scenario 10:	Catalytic reforming unit (CRU)	-0.5	0.8	1.7	2.9
Scenario 11:	Energy efficient pumps	-262.5	-255.0	-249.6	-242.2

The technical energy saving and GHG mitigating potential achievable through the integration of each energy saving option into the system were calculated for both mid- and long-term time planning horizons (i.e., 2030 and 2050 scenarios, respectively). In addition, we calculated the net present value (the system-level net economic impact of the energy saving option over the time period of the study) and the cost per tonne of saved carbon. For this, we considered the carbon cost applicable to large-scale industrial emitters through the Alberta Carbon Competitiveness Incentive Regulation (CCIR). The CCIR includes all the large-scale industrial plants with annual emissions of 100,000 tonnes or more in or after 2003 [364]. Among the existing refineries in Alberta (Table 5-6), Imperial Oil, Shell Scottford, and Suncor refinery in Edmonton are included the CCIR [365].

Table 5-6: Alberta operating refineries & their feedstocks (2016)

Refinery	Feedstock	Production capacity (bbl/day) [366, 367]	GHG emissions (Ktonne CO_2eq) [200]
Suncor Edmonton	Sweet & sour SCO[22]	142,000	1316.43
Imperial Oil Edmonton	Conventional oil	187,200	1547.09
Shell Scotford	SCO from the adjacent Shell Scotford upgrader	100,000	844.78
Husky Asphalt Refinery	SCO from the Lloydminster upgrader	29,000	94.22

In the CCIR, emissions are allocated to an industrial plant based on its performance against the benchmark that is defined for the specific industrial sub-sector [368]. Similar to other carbon-intensive industries, the CCIR has established a benchmark for petroleum refining in the province and provides guidelines for carbon pricing in the sector (Table 5-7).

Table 5-7: Established benchmark for petroleum refining sector [369]

Year	2018	2019	2020	2021	2022	2023 and subsequent years
Benchmark value tonne CO_2eq per Alberta CWB[23]*1000	**3.831**	**3.831**	**3.793**	**3.755**	**3.717**	**BE_Y-BE_{Y-1}-0.038**

[22] Synthetic crude oil

In Table 5-7, BE_Y and BE_{Y-1} shows the established benchmark for current and the previous year for which the emissions are calculated, respectively.

We used this benchmark data to calculate the amount of taxable emissions (i.e., above the defined threshold) and applied the carbon price to assess the monetary values associated with that. The suggested carbon price is included in the LEAP model as external cost and its impacts on the price of saved carbon were assessed. The scenario-specific energy saving potential, GHG emissions profile, and technology implementation costs are presented in Table 5-8.

[23] "Complexity-Weighted-Barrel: is an equivalent barrel divisor for refinery throughput indicative of GHG emissions potential based on a refinery's configuration and processing complexity"

Table 5-8: Results of the LEAP model

Energy efficiency improvement scenarios	Fast penetration scenario (2010-2030)				Slow penetration scenario (2010-2050)			
	Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV & GHG abatement cost		Cumulative energy saving& GHG mitigation compared to reference scenario		Incremental NPV& GHG abatement cost	
	Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq.	Energy (PJ)	GHG (Mtonne)	NPV (m CAD)	CAD/ tonne of CO_2eq
Crude distillation unit (CDU) – Heat integration	8.82	0.56	0.02	0.04	18.44	1.17	2.44	2.08
Crude distillation unit (CDU) – Combustion air preheating	21.14	1.34	13.38	9.96	44.28	2.81	23.83	8.47
Vacuum distillation unit (VDU)	5.24	0.33	-7.13	-21.43	11.01	0.70	-9.77	-13.97
Delayed coking unit (DCU)	0.80	0.08	-2.38	-29.97	1.68	0.17	-3.05	-18.42
Fluid catalytic cracking (FCC)	0.49	0.1	-2.05	-21.18	1.02	0.20	-3.03	-15.33
Alkylation unit (AU)	11.63	0.65	-38.88	-59.77	24.36	1.36	-41.29	-30.31
Isomerization unit (IU)	7.28	0.41	-59.07	-145.08	15.33	0.86	-67.92	-79.24
Hydrocracking unit (HCU)	3.83	0.24	-3.89	-16.02	8.06	0.51	-3.43	-6.69
Hydrotreating unit (HTU)	11.64	0.74	-207.83	-281.06	24.34	1.55	-242.41	-156.74
Catalytic reforming unit (CRU)	2.41	0.13	-2.4	-17.82	5.04	0.28	-3.09	-10.96
Energy efficient pumps	7.18	0.11	-7584	-679.00	14.84	0.13	-85.78	-638.35

While the data in Table 5-8 provide invaluable information about the technical and economic performance of individual energy efficiency options, we have used them further to develop carbon abatement cost-curves.

5.4.4. GHG abatement cost curve

The cost curves show incremental abatement cost estimates required to avoid a certain amount of GHGs (in CAD/tonne of CO_2 mitigated). The GHG abatement cost is the difference between the cumulative costs of the system in the energy efficiency scenario and baseline scenario. The costs are calculated over the time periods of the study (i.e., 2010-2030 and 2010-2050 for the fast and slow penetration scenarios, respectively). The cost is further calculated in terms of the per unit GHG mitigation potential of the efficient technologies compared to the existing ones. The overall GHG abatement costs are the incremental costs of the alternative scenario compared to the baseline scenario per unit GHG mitigated. The mitigation potential is cumulative over the planning horizons of the study (i.e., 2010-2030 and 2010-2050).

The GHG mitigation cost for each energy saving option and the cumulative GHG mitigation potential of the different scenarios are shown in Figure 5-11 and Figure 5-12. In the graphs, the horizontal axis shows the cumulative emissions reduction and the vertical axis shows the cost of emissions reduction (in CAD) per tonne CO_2 reduction. In other words, the width of the bars represents the cumulative mitigation potential and the height shows the associated GHG mitigation cost (incremental NPV/tonne CO_2 reduction). The bars in Figure 5-11 and Figure 5-12 represent the different GHG mitigation scenarios. For the bars below the horizontal axis, the GHG abatement cost is negative and attractive. For those above the horizontal axis, there is a cost associated with implementing the options.

As shown in Figure 5-11 (for the fast penetration scenario), the cumulative GHG mitigation potential over the time horizon 2010-2030 is 4.91 Mtonnes CO_2 eq. The cumulative emissions in the baseline scenario were calculated to be 97 Mtonne CO_2 eq. over the time period of study. In other words, the simultaneous implementation of energy efficiency options in the refining sector would help reduce GHG emissions from the sector by 5.1% by 2030. The GHG mitigation costs for different measures range from -697 CAD/tonne CO_2 eq. for implementing energy-efficient pumps to 9.96 CAD/tonne CO_2 eq. for air preheating in the crude distillation unit. Almost 80% of the emissions reduction is achievable through implementing energy saving options in the CDU, hydrotreating, alkylation, and isomerization units. In terms of economic performance, 60% of emissions can be reduced with negative cost (i.e., the economic benefits exceed the implementation costs) which indicates the attractiveness of the options.

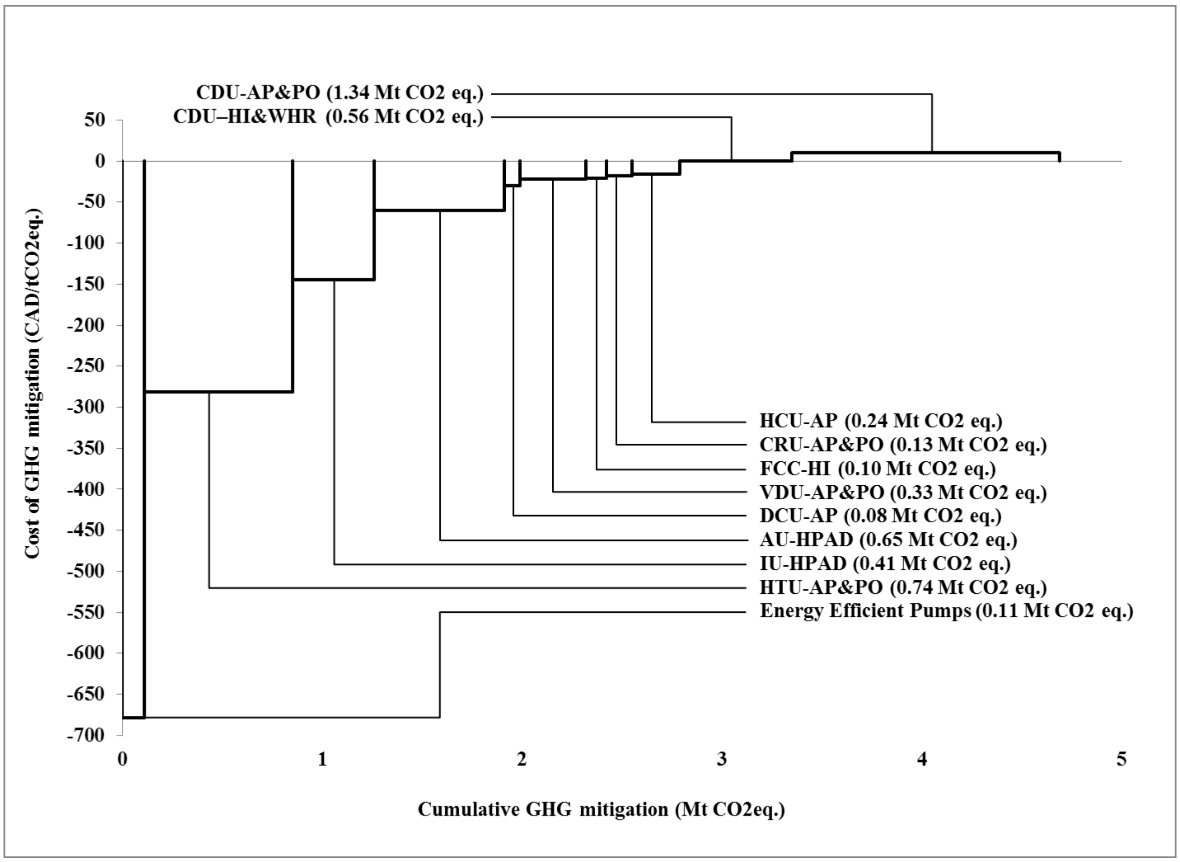

Figure 5-11: GHG abatement cost curve (fast penetration scenario, 2010-2030)

The GHG abatement cost curve for the slow penetration scenario is shown in Figure 5-12. As shown in the figure, over the time horizon 2010-2050 the cumulative GHG mitigation potential is 9.74 MTonne CO_2 eq., or 5.3% of the baseline scenario emissions by 2050. The GHG mitigation costs range from -638 CAD/tonne CO_2 eq. for energy efficient pumps to 8.47 CAD/tonne CO_2 eq. for air preheating in in the crude distillation unit. Similar to the fast penetration scenario, the majority of CO_2 mitigation can be achieved by implementing energy efficiency measures in the CDU, HRU, alkylation, and isomerization units. More than 59% of emissions can be reduced with negative cost.

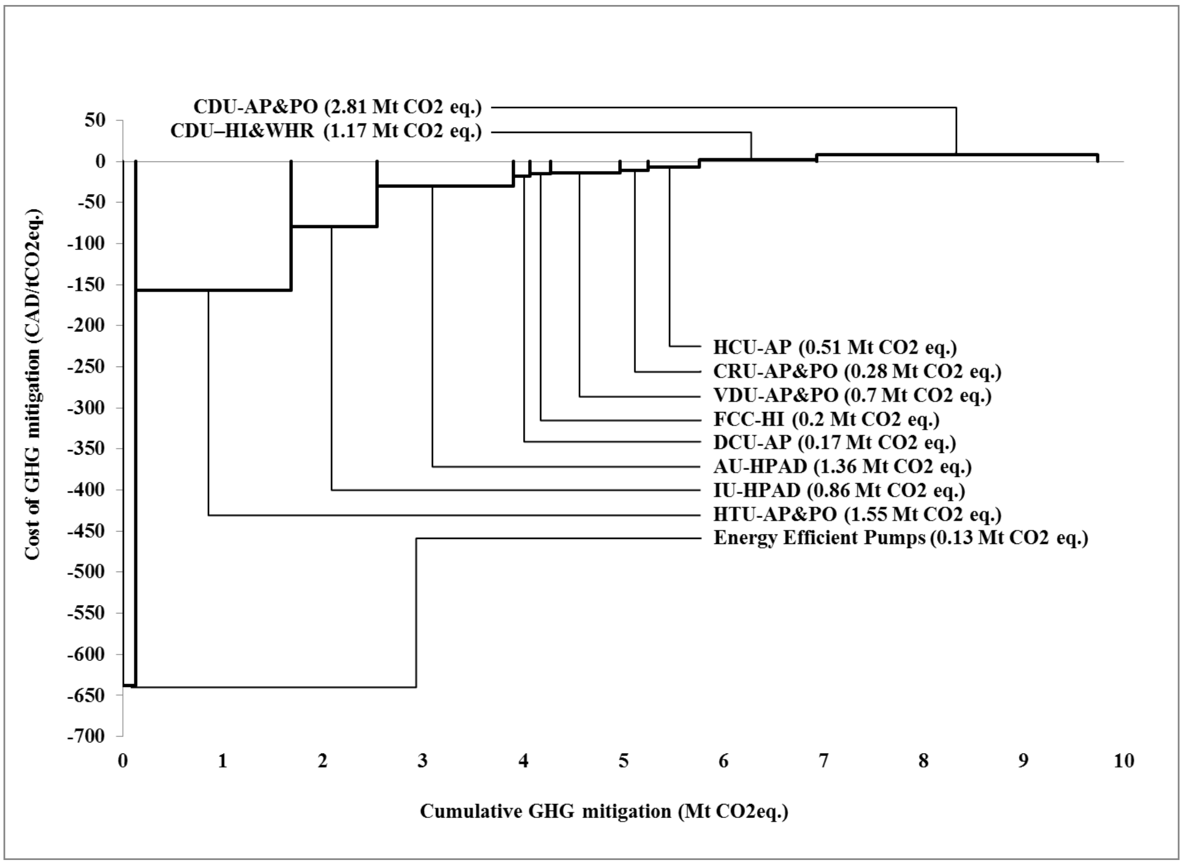

Figure 5-12: GHG abatement cost curve (slow penetration scenario, 2010-2050)

While the GHG mitigation potential in the refining sector is reported to be between 10 and 20% [370], the energy efficiency improvement share in overall GHG mitigation from the sector is calculated by Chan et al. to be marginal [351]. In other words, the effects of energy efficiency improvement on the sector's GHG mitigation are limited and substantial GHG reduction can be achieved only through technologies such as solar and carbon capture and storage [371-373]. This is mainly because a significant portion of energy efficiency potential in the refining sector has been already realized by the industry [374]. For example, in Canada, large petroleum refineries such as Shell and Petro-Canada started implementing energy efficiency measures in the 1990s [375].

5.4.5. Sensitivity analysis

We analyzed the sensitivity of the results to the input variables by assessing the impacts of discount rate, fuel price, and carbon price on the GHG abatement cost in different scenarios in the 2030 time horizon. Assumptions for the fuel prices and carbon price that are used for sensitivity analysis and the observations from the sensitivity analysis are presented in this section; detailed results of the sensitivity analysis are presented in Appendix VI-II.

5.4.5.1. Discount rate

In order to account for the time value of money, we considered a discount rate and nominal inflation rate of 5% [80] and 2% [376], respectively. In other words, for the initial analysis, a real discount rate (i.e., nominal discount rate-inflation rate) of 3% was considered in the analysis. To assess the sensitivity of the results to this assumption, a range of ±10% was considered. The results of the analysis suggest that a ±10% fluctuation in the nominal discount rate (i.e., nominal rate of between 4.5% and 5.5%) will have minimal impacts on the GHG abatement cost for different scenarios. More specifically, the changes in the GHG abatement cost due to the change in the discount rate will be limited to ±7% for all the scenarios except for the CDU heat integration scenario, where the impact of a change in discount rate will result in a ±13% change in the GHG abatement cost. In summary, we found that changes in the discount rate will impact neither relative GHG abatement cost for different scenarios nor the percentage of overall GHG mitigation achievable with negative cost.

5.4.5.2. Fuel price

Industrial end-use energy price projections by the National Energy Board (NEB) were used in this study to calculate the cost of saved energy and the GHG abatement cost [282]. In order to analyze the sensitivity of the results, in addition to the reference fuel price scenario, we also considered the NEB's high and low fuel price projections (Table 5-9).

Table 5-9: End-use industrial fuel price (CAD/GJ) [282]

Fuel price scenario	Fuel	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Reference	Electricity	20.0	25.3	29.4	32.8	31.8	30.3	30.1	29.8	29.7	29.6	29.8	32.3	33.0	35.1	35.1	35.1	38.8	39.3	40.0	40.3	43.5	40.7	40.5	40.7	40.2	40.0
	Natural Gas	3.5	3.2	1.8	3.0	3.1	3.2	3.3	3.4	3.6	3.8	3.9	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.8	4.9	5.0	5.0	5.1	5.2	5.3
	Light Fuel Oil	13.1	15.6	15.8	15.6	15.6	15.6	15.9	16.1	16.3	16.6	16.8	16.9	17.0	17.1	17.2	17.3	17.3	17.4	17.5	17.6	17.7	17.8	17.9	18.0	18.0	18.1
High	Electricity	20.0	25.3	29.4	32.8	31.6	30.6	30.8	30.5	30.5	30.5	34.4	38.8	39.5	40.0	42.9	43.4	43.4	44.4	45.5	49.5	52.6	50.4	45.8	46.7	46.6	46.2
	Natural Gas	3.5	3.2	1.8	3.1	3.8	4.7	4.8	4.9	5.1	5.3	5.4	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.3	6.4	6.5	6.5	6.6	6.7	6.8
	Light Fuel Oil	13.1	15.6	15.8	18.3	20.6	20.6	20.8	21.0	21.3	21.5	21.8	21.8	21.9	22.0	22.1	22.2	22.3	22.4	22.4	22.5	22.6	22.7	22.8	22.9	23.0	23.1
Low	Electricity	20.0	25.3	29.4	32.8	31.6	30.2	30.0	29.7	29.6	29.4	29.4	29.4	29.3	29.1	29.0	28.9	30.5	32.7	35.4	35.7	36.6	36.2	36.0	36.2	36.1	35.9
	Natural Gas	3.5	3.2	1.8	2.9	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.3	3.4	3.5	3.5	3.6	3.7	3.8
	Light Fuel Oil	13.1	15.6	15.8	13.3	10.7	10.7	10.9	11.2	11.4	11.6	11.9	12.0	12.1	12.1	12.2	12.3	12.4	12.5	12.6	12.7	12.8	12.8	12.9	13.0	13.1	13.2

The results suggest that the range of changes in the GHG abatement cost is the smallest for heat integration in the fluid catalytic cracking scenario (i.e., 2.42 CAD/tCO_2eq. and 9.78 CAD/tCO_2eq. for the low and high fuel price scenarios, respectively). On the other hand, the largest fluctuation was observed for the heat integration in the catalytic reforming unit scenario, where GHG abatement cost fluctuates between -4.71 CAD/tCO_2eq. and 30.03 CAD/tCO_2eq. for the low and high fuel price scenarios, respectively. The fuel price was also found to impact the overall economic performance of various scenarios. While the percentage of achievable GHG mitigation with negative cost is similar in the low and reference fuel cost scenarios, in the high fuel cost scenario, 100% of the GHG emissions reduction is achievable with negative cost. In other words, the higher price of energy carriers was found to positively impact the economic attractiveness of GHG mitigation options.

5.4.5.3. Carbon price

The current carbon price in Alberta is CAD 30/tonne CO_2eq. and is set to increase in the coming years (i.e., to CAD 40/tonne CO_2eq. and CAD 50/tonne CO_2eq. in 2021 and 2022, respectively) to comply with the federal price of carbon. In the current analysis, we assumed that the price of carbon will remain constant after 2022.

In order to assess the sensitivity of the results to this assumption, we considered two carbon price scenarios. In one, we assumed there will be no cost for GHG emissions from petroleum refining and in the other; we considered that after 2022 the cost of carbon will increase in CAD 10/tonne CO_2eq. increments until it reaches CAD 100/tonne CO_2eq. in 2027 (Table 5-10).

Table 5-10: Carbon Price (CAD/Tonne CO_2)

Carbon price scenario	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Confirmed carbon Price	30	30	30	40	50	50	50	50	50	50	50	50	50
High Carbon Price	30	30	30	40	50	60	70	80	90	100	100	100	100

As expected, in the no-carbon cost scenario the GHG abatement cost is higher for all GHG mitigation scenarios compared to the reference scenario. The results also suggest that in the no-carbon cost scenario, the GHG abatement cost will increase to CAD 1.76/tonne CO_2eq. (compared to CAD -16.02/tonne CO_2eq.) in the reference-carbon cost scenario. In other words, if no carbon cost is imposed on the refining sector, only 56% of the overall mitigation potential is achievable with negative cost, compared to 61% in the reference-carbon cost scenario. On the other hand, if the cost of carbon increases to CAD 100/tonne CO_2eq., the GHG abatement cost in the CDU heat integration scenario will fall to CAD -9.21/tonne CO_2eq. (compared to CAD 0.04/tonne CO_2eq. in the reference-carbon cost scenario), which means that in this case 73% of the overall mitigation potential is achievable with negative cost.

In conclusion, the results of sensitivity analysis suggest that while discount rate has minimal impact on the overall economic performance of GHG mitigating options, the impacts of fuel price and carbon costs are considerable. Of the two, fuel price was found to have the highest impact, and if the NEB high fuel price scenario is to occur, 100% of the overall mitigation potential is achievable with negative cost.

5.4.6. Implication for policy

In order to develop the industrial benchmark, the total regulated emissions including the facilities' combustion emissions, imported and exported emissions from the facility, and the CO_2 use within the facility need to be calculated [377]. The energy consumption demand tree developed in this study provides invaluable insights for the energy consumption and GHG emissions at process/technology level within the refining sector and therefore can be effectively used to develop and revise existing petroleum refining sector CCIR benchmarks.

In jurisdictions such as Canada, where both conventional and oil sand refineries (with different energy and carbon intensity) exist, establishing an industry-wide benchmark (as currently exists in Alberta) has both advantages and disadvantages. On the positive side, the industry-wide benchmark provides incentive to oil sands refineries to reduce their emissions intensities further to compete with the conventional refineries with approximately 17% lower energy intensity. This will result in the sharp reduction of emissions from the industry as a whole and help the province reach its ambitious targets of emissions reduction as outlined in the Alberta Climate Leadership Plan [208]. On the other hand, it might adversely impact the economic competitiveness of oil sands refineries as they have to invest more in emissions reduction than do conventional oil refineries.

The current industrial carbon regulation in Alberta (CCIR) does not include refining plants with the GHG emissions of less than 100,000 tonnes per year. Thus Husky Energy's refinery is not included in the CCIR program because its emissions are below the emissions threshold limits. This is despite the findings from the energy consumption demand tree where we found that the plant refines relatively heavy feedstock and is more energy- and carbon-intensive than conventional refineries (Section 5.3.2.1). Although this refinery accounts for only 6% of

Alberta's refining capacity, including the plant in the CCIR program will not only incentivize its emissions reduction but also help economic competitiveness among all the stakeholders in the sector.

The results also suggest that more than 60% of the GHG mitigation potential from the sector is achievable with negative cost. Information campaigns and familiarizing industrial stakeholders with this potential can facilitate the implementation of the identified energy efficiency measures within the sector. Also, the price of fuel and price of carbon is an important factor than can positively impact the economic attractiveness and therefore the adoption rate of the identified energy efficiency measures within the system.

5.5. Conclusion

An integrated process modeling and resource planning framework was developed in this study that uses the results of process simulation to develop long-term GHG mitigation strategies at the system level. The comprehensive and data-intensive refining model developed in this research can be used to study the future development of the refining sector in other jurisdictions. In addition, the model provides a flexible platform in which the impacts of the integration of various energy efficiency options, as well as emerging technologies on systems-level GHG emissions, can be assessed and further applied for policy making. For Alberta, the continuation of historical trends and the government plans for capacity development would result in a sectoral increase of 8% in GHG emissions (from 2010 levels) by the end of 2050. A process model of the refinery was developed and eleven energy efficiency options were assessed and classified into four categories: heat integration, process optimization and preheating the combustion air, the application of new technologies (i.e., heat pumps), and the use of energy-efficient equipment (i.e., pumps). The results of process simulation (i.e., of the identified energy efficiency options) were used to develop GHG mitigation scenarios in the LEAP model. The scenario analysis results suggest that compared to the baseline scenario, the simultaneous implementation of energy efficiency options would help reduce cumulative GHG emissions from the sector by more than 5%. The cost of GHG mitigation varies among the options. The GHG abatement cost is from -679 CAD/tonne CO_2eq. to CAD 10/tonne CO_2eq. in the slow penetration scenario and from -638 CAD/tonne CO_2eq. to CAD 8.5/tonne CO_2eq. in the fast penetration scenario. For both scenarios, almost 61% of the anticipated GHG emissions reduction potential can be achieved with negative cost. The use of energy-efficient pumps was identified to be the most economically attractive GHG mitigation option. It was also found that most of the GHG mitigation can be achieved by implementing energy efficiency measures in the crude distillation, hydro-treating, alkylation, and isomerization units.

Chapter 6 : Assessment of Long-term Energy Efficiency and Greenhouse Gas Emissions Mitigation Potential in the Chemical Sector: A Canadian Case Study[24]

6.1. Introduction

The industrial sector accounts for more than one-third of global energy consumption and greenhouse gas (GHG) emissions [102, 118]. Energy consumption in industries increased more than 66% between 1971 and 2014 [378]. With historical annual average increases of 2.2% in energy consumption [118], in 2011 the chemical sector accounted for almost 28% (including feedstock) of total energy consumption in the industrial sector globally[25] [102]. In terms of cost, energy can be up to 60%-80% of total production costs in the chemical industry [118]. High levels of energy consumption, along with associated environmental impacts and costs, highlight the importance of energy conservation in the sector.

6.1.1. Brief literature review

The existing literature on energy efficiency improvement in the sector generally focuses on the major energy consumers such as the petrochemical and fertilizer sub-sectors. Some of these studies focus on specific energy efficiency technologies. For example, Ren and Patel (2009) compared the energy and emission intensity of petrochemical products using different

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[24] A version of this chapter was published as Talaei A, Ahiduzzaman M, Kumar A. "Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation potentials in the chemical sector." Energy, 2018; 153: 231-247.

[25] i.e., in 2011, total energy consumption in the chemical sector was reported to be 949 Mtoe.

conventional and biomass feedstock [222]. In a study by International Energy Agency (IEA), it was found that catalytic processes could help reducing the energy intensity of chemical processes by 20-40% in long term and also highlights the importance of biomass and renewable hydrogen for deep reduction of emissions from the sector [223]. Innovative technologies for application in naphtha cracking process (as the most energy intensive process in chemical industry) were analyzed by Ren et. al., (2006) where the results suggest a 20% energy intensity improvement potential in the process [224]. Similarly, the impacts of demand-side management (application of energy efficiency motors) and on-site cogeneration technology on the overall energy consumption of the chemical plants were assessed in by Pillay and Fendley [225] and Szklo et. al. [226], respectively. Menezes et al., (2017) assessed the economic feasibility of steam traps and insulation for energy efficiency improvement in the steam system of a petrochemical plant in Brazil [379].

Other studies assess the implementation of energy efficiency measures through high-level scenario and policy analyses. For example, Fan et al., used decomposition analysis to evaluate the impacts of industry output, structure of industry and the technical factors on the GHG emissions from China’s petrochemical industry [380]. Griffin et al., identified the opportunities for reducing energy demand and emissions reduction in the UK chemical sector. The high-level approach used in that study has led to qualitative analysis of the short- to mid-term (process improvement, process substitution and carbon sequestration) and long-term (i.e., utilization of biomass as feedstock) energy efficiency improvement options in the sector [381]. Chan et al., identified the major energy consuming chemical sub-sectors in Taiwan and compared their energy intensity with the global best practices to assess the energy intensity improvement potential [382]. Levi and Cullen, analyzed the flows of chemical from resources to final products and highlighted the importance of martial flow analysis for GHG emissions mitigation [383]. Ren, analyzed the barriers and drivers of energy efficiency improvement in chemical industry [384]. Zhou et. al., developed different scenarios to estimate the GHG mitigation potential in China's ammonia industry. In that study, a top-down approach focusing on the fuel consumption with less emphasize on technological energy efficiency improvement was applied for scenario analysis [385]. The long-term impacts of different energy efficiency clusters on sectoral GHG emissions were quantified thorough developing three top-down scenarios in the UK [386] and in Thailand [387].

Review of the literature suggests that application of technology-level analysis to develop system-level energy efficiency strategies is less common in the studies which focus on chemical sector. A few studies assessed overall energy saving potential in the industry at the systems level.

Table 6-1 provides an overview of existing studies on different aspects of energy savings in the chemical sector.

Table 6-1: Summary of chemical sector energy efficiency studies

Study purpose	Industry subsector	Methodology	Geographical jurisdiction	Ref.
Analysis of energy efficiency potential.	Petrochemical	Comparison of actual and theoretical energy consumption in petrochemical plants.	Western Europe; the Netherlands; the world	[229]
Analysis of the impacts of catalytic processes on energy consumption and the technology roadmap in the chemical industry.	Chemical	Process analysis.	global	[223]
Development of a benchmark for industrial energy consumption.	Different industries including chemical	Comparison of actual and reference-specific energy consumption in selected industries.	The Netherlands	[230]
Analysis of the innovative approaches for reducing energy consumption in steam cracking.	Chemical	Analysis of state-of-the-art technologies for energy saving in the steam cracking process.	NA	[224]
Assessment of energy saving potential in the Dutch ammonia industry.	Fertilizers	Analysis of different energy saving measures in the ammonia industry and their economic feasibility (bottom-up approach).	The Netherlands	[388]
Assessment of the penetration potential of renewable energies in the industrial sector.	Different industries including chemical	Industrial-level techno-economic assessment.	global	[389]
Analysis of process innovation and efficiency improvement.	Petrochemical	Policy analysis.	NA	[384]
Assessment of the impacts of modern electric motors on energy saving.	Petrochemical and petroleum refining	Cost-benefit analysis.	Louisiana, US	[225]
Assessment of GHG mitigation in the ammonia industry though fuel switching and technology innovation.	Fertilizers	Scenario analysis.	China	[390]
Estimation of energy saving potential in the chemical industry	Chemical industry	Scenario development and policy analysis.	China	[391]
Assessment of the potential for cogeneration technology in the chemical sector.	Chemical sector	Techno-economic assessment.	Brazil	[226]
Assessment of energy saving potential.	Petrochemical sector	Comparison of energy consumption for petrochemical production using different feedstock and technologies.	NA	[222]
Analysis of energy efficiency potential.	Chemical and petrochemical sectors	Development of energy efficiency indicators and comparison of actual data with best practices.	global	[231]
Analysis of the status of energy consumption.	Chemical sector	Process analysis of different sub-sectors of the industry.	United States	[392]

As

Table 6-1 shows, a limited number of studies use a buttom-up approach to analyze energy consumption in a system as a whole. A bottom-up approach provides the opportunity to assess energy consumption at a process/facility level, from which a systems-level analysis could be conducted. Despite the proven features for system analysis [32, 81], application of buttom-up energy modelling techniques for industrial sector is limited. This is basically due to the complexity of the industrial sector, variations in industrial products, and the role of energy carriers both as a source of energy and in some industries as a feedstock.

6.1.2. Aims and objectives

The current study aims at addressing the existing gap in the literature and developing a comprehensive bottom-up framework to analyze the energy efficiency improvement and GHG mitigation potential from chemical industry and its associated cost in mid- to long-term. To this end, a combination of techniques including energy modelling and scenario analysis, techno-economic assessment and policy analysis are applied. The specific objectives of this research are to:

- Develop a comprehensive and flexible framework for analyzing the long-term GHG mitigation from different industrial sectors.
- Apply the framework and develop a data-intensive, technology-rich and transferrable model to analyze the process-level energy consumption in different chemical sub-sectors;
- Identify the major energy consuming sub-sectors and the areas with potential for energy efficiency improvement;
- Identify the process-level energy savings technologies within the chemical sector;
- Assess the applicability of the energy saving options and their potential for GHG system-level GHG mitigation in mid-to long-term;

- Analyze the economic performance of different energy efficiency options; and
- Develop an emissions reduction cost curve to assess and prioritize options based on their GHG mitigation potential and on associated cost.

In order to meet these objectives, a case study was conducted for Alberta's (a western province in Canada) chemical sector. In Alberta, the sector is responsible for 12% and 9.6% of industrial energy consumption and GHG emissions, respectively. The considerable GHG emissions from the chemical industry and the expected increasing trend make the sector one of the most important areas to achieve GHG mitigation.

To the author's knowledge, currently there is no study exist in the literature that assesses the long-term energy efficiency improvement and GHG mitigation potential in the Canadian chemical sector. Therefore, the contribution of the of the current work is two-folded: a) to develop a comprehensive and data intensive frameworks which is flexible and transferable to study the long-term GHG mitigation potential from chemical sector in other jurisdiction and b) to conduct and case study and analyze the low-carbon pathways through which the Alberta's chemical sector would develop.

The next section provides an overview of the methodology and the developed framework for the analysis. The case study and the steps involved in applying the framework to analyze the long-term GHG mitigation from the industry are discussed in Sections 6.3 and 6.4, respectively. Results are presented in Section 6.5. Section 6.6 is the conclusion.

6.2. Methodology

6.2.1. The LEAP model

We used The Long-range Energy Alternative Planning (LEAP) model (version 2015.0.19.0) [393]. LEAP is an energy modelling and policy development framework that can model different stages of the energy system from energy extraction from resources to the energy consumption in the demand sector. In addition, the scenario management module in the LEAP model provides the opportunity to analyze individual policy measures and assess different pathways for future energy system evolution [32]. Furthermore, LEAP has a built-in Technological and Environmental Database (TED) where the detailed environmental impacts of different processes and fuel combustion are available. The TED database can be modified based on the specific characteristics of the process. In other words, the emission factors for energy consumption could be altered depending on the specific process characteristics and also characteristics of the consumed fuel. These features provides capabilities to LEAP to analyze the mid- to long- term development of the energy system in different sectors

6.2.2. LEAP model for Alberta

A detailed energy system model is developed for both energy supply and demand sectors in Alberta. This provides the opportunity to account for the life cycle emission (e.g. from electricity generation sector) associated with the final product [66]. In addition, simulation of the energy supply system development provides the opportunity to account for the impacts electricity sector decarbonization strategies and their impacts on the GHG emissions at the demand side.

6.2.3. Framework for analyzing the GHG emissions in the industrial sector

Figure 6-1shows the overview of the framework that is used for analyzing the long-term GHG long-term GHG mitigation potential in the industrial sector. As the first step in the analysis and in order to assess the current performance of the industry, an energy consumption demand tree was developed. The energy consumption demand tree helps identifying the major energy consuming sub-processes and their energy intensities (i.e., energy consumption per unit of final product). Following the analysis of the current status of the system, a baseline scenario was developed to project the sectoral development pathways and assess the associated energy consumption and GHG emissions. In addition, several mitigation scenarios (each associated with energy efficiency improvement in various sub-processes in the chemical sector) were developed to assess the achievable GHG reduction potential from the sector. In order to analyze the incremental costs of implementing energy efficiency measures (i.e., mitigation scenarios), a cost benefit analysis was conducted. Then the incremental costs and the GHG reduction potential were used to develop emissions mitigation cost curves, which help understand the cost to mitigate one tonne of carbon by a particular technology over a particular period of time

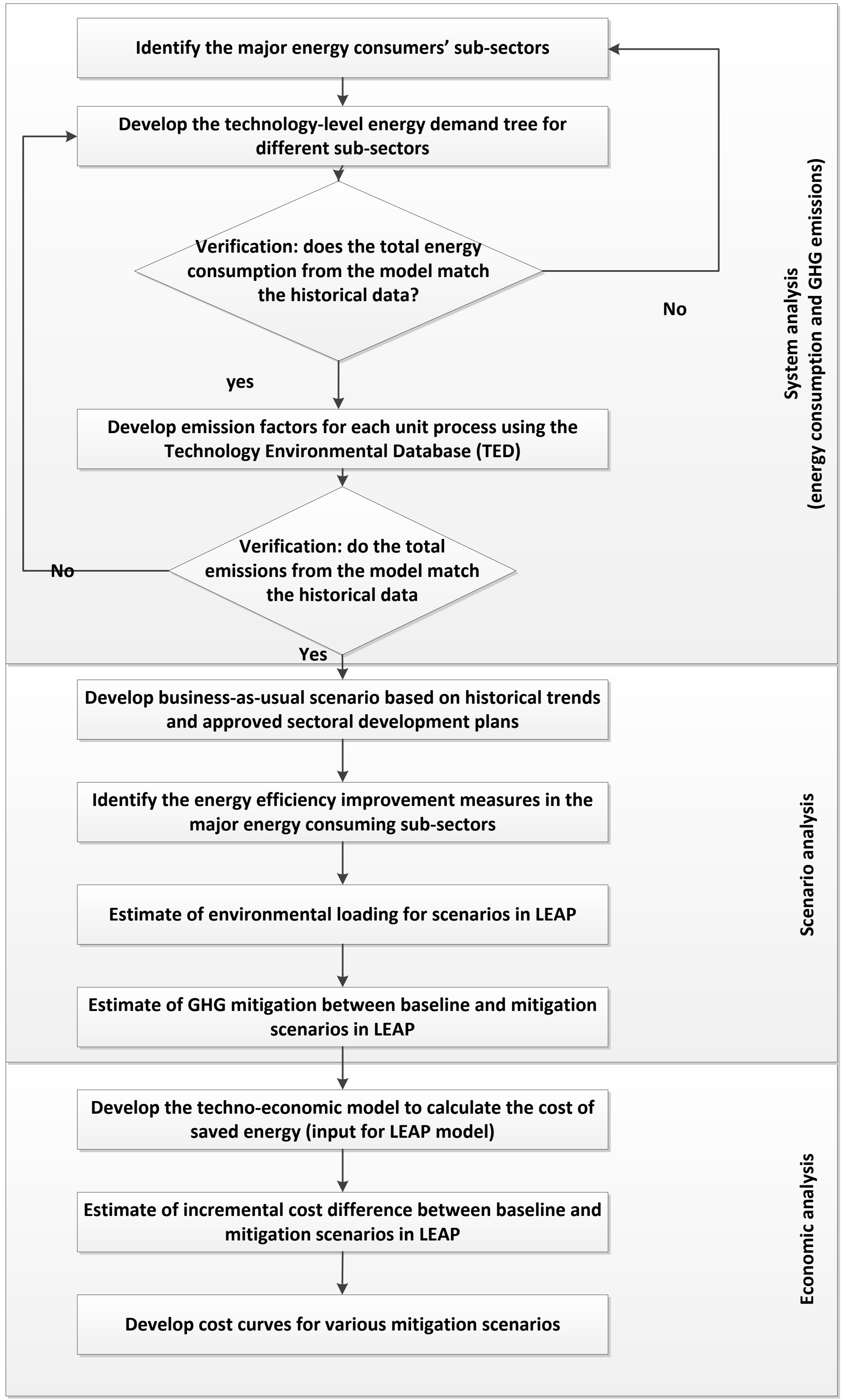

Figure 6-1: Overview of the methodology for developing GHG mitigation cost curve

The cost curve shows the incremental GHG mitigation potential and its associated cost for any specific GHG mitigation scenario. The net present value (NPV) of the costs associated with implementing energy saving measures and the calculated GHG mitigation (given in megatonnes of CO_2 equivalent) are used to develop the emissions abatement cost curves. In order to calculate the NPV for each scenario, different components of cash flow (i.e., capital cost, operating and maintenance [O&M] cost, and fuel costs) were considered and discounted over the time period of the study.

An external techno-economic model was developed to calculate the cost of saved energy (used as input for the LEAP model). In the model, data on existing and energy efficient technology costs (both capital and O&M costs), energy saving potential, and macro-economic data (i.e., discount rate, industry development predictions, and fuel price for different energy carriers) were used to calculate the cost of saved energy. These calculations were made using 6-1:

$$\boldsymbol{CSE} = \frac{\sum(\boldsymbol{C}_{\boldsymbol{EE}} - \boldsymbol{C}_{\boldsymbol{Base}}) + \sum(\boldsymbol{O\&M}_{\boldsymbol{EE}} - \boldsymbol{O\&M}_{\boldsymbol{Base}}) + \sum(\boldsymbol{F}_{\boldsymbol{EE}} - \boldsymbol{F}_{\boldsymbol{Base}})}{\sum \boldsymbol{EC}_{\boldsymbol{Base}} - \boldsymbol{EC}_{\boldsymbol{EE}}} \qquad \textbf{Equation 6-1}$$

In the equation, EE and Base are the energy efficiency and existing technologies, respectively. C is the technology's capital cost, O&M is the operating and maintenance cost (excluding the fuel cost), and F is energy consumption cost. EC is the energy consumption of each technology.

In equation 1, capital cost shows the fixed one-time investment that occurs at the time of implementing the technology. This cost re-occurs only at the end of the lifetime of the technology when the energy efficiency technology needs to be replaced. O&M cost refers to the cost associated with operation of the unit. O&M has both fixed and variable cost components. Examples of O&M costs are labor cost, regular maintenance cost and fuel cost. In the current analysis the cost of fuel is considered as a separate component and is not included in the O&M.

In order to account for the time value of money discount rate of 5% and inflation rate of 2% is considered in the analysis. All the cost factors were annualized using the discount factor, and the lifetime of the technologies was also considered details of which is provided in Appendix V.

6.3. Case study of Alberta's chemical sector

Alberta, the energy capital of North America, is home to large industrial plants. Of all the industries in Alberta, the chemical industry is the second biggest contributor to both energy consumption and greenhouse gas (GHG) emissions (second only to the mining sector). The main products from Alberta's chemical sector include petrochemicals, pesticides and fertilizers, industrial gases, and organic and inorganic chemicals. Of the 8.6 billion pounds of petrochemicals are produced annually [394, 395], ethylene is the main product (51.6% mass basis) [396] followed by styrene, propylene, and benzene with shares of 9.5%, 6.4% and 5.5%, respectively. Very few formulated products and specialty chemicals (FPSCs) are manufactured [397].

6.3.1. Identification of the most energy- and GHG-intensive sub-sectors

Currently, available data on energy end uses and on energy intensities of equipment/devices used in Alberta's chemical sector are limited. Only cumulative energy consumption data of various types of energy are available (i.e., total annual consumptions of natural gas, electricity, etc.). This level of data makes it difficult to identify the most energy-intensive sub-sectors and assess the energy efficiency and GHG mitigation potential in the industry. To evaluate the GHG mitigation potential in the chemical sector, it is critical to understand the current performance of the industry's sub-sectors in term of both energy consumption and GHG emissions.

The major energy consumers in the chemical industries were identified through a bottom-up approach and considered for detailed analysis. Specific energy consumption (SEC) and production levels were used as the decision factors to identify the biggest energy consumers.

Based on process energy intensity and production level, the petrochemical (ethylene production subsector) and fertilizer (ammonia production subsector) sectors were chosen for further investigation in this study.

6.4. Model development

We used publically available data from key provincial and federal agencies to develop the LEAP model for Alberta. Some of the main institutions from which the data were acquired are the National Energy Board (NEB), Natural Resources Canada (NRCan), the Chemistry Industry Association of Canada (CIAC) as well as Statistics Canada's CANSIM tables and other similar databases. A detailed model was developed for the province of Alberta in Canada. While the comprehensive and data-intensive model covers all stages within the energy system (i.e., resources, transformation and demand side), the main focus of the current study is the chemical sector in the demand side.

Modelling was done in different stages for both the ethylene and ammonia production sectors. The stages are demand tree development, base year data collection, model verification and scenario analysis.

6.4.1. Demand tree development

Energy is consumed in different chemical sub-sectors. An energy consumption demand tree helps identify the major energy consuming sub-sectors and provides insights on the identified sectors for energy efficiency improvement. In the following sections, the development of demand trees for ethylene and ammonia production processes is discussed in detail.

6.4.1.1. Ethylene production

Thermal cracking of alkanes such as ethane, naphtha, and butane is the commonly used method of ethylene production [222, 224]. In Alberta, however, steam cracking of ethane is the main method for ethylene production[26]. In terms of process design, the cracking of ethane and naphtha for ethylene production is almost identical (except for the separation and compression processes) [224]. Of all feedstocks, steam cracking of ethane is the most efficient for producing ethylene (Table 6-2). In the ethylene production process, steam cracking is the most energy intensive sub-process. Worldwide, about 40% of the chemical and petrochemical industries use final energy for the steam cracking process [398].

Table 6-2: Influence of feedstock on yield for ethylene production (weight %) [392]

Feedstock	Ethane	Propane	Butane	Naphtha	Atmospheric gas oil	Vacuum gas oil
Ethylene yield (%)	78	42	40	34	26	21

A simplified ethane cracking process diagram is shown in Figure 6-2. Compared to other feedstocks, ethane cracking requires higher temperatures in the furnace, the capacity of a C_2 splitter, and fewer infrastructure facilities. No additional recovery equipment for propylene is required. Several byproducts are generated during ethylene production. However, when ethane is the feedstock used, almost no propylene, butadiene, or aromatics are formed [392].

[26] In European countries, naphtha is the main feedstock in the ethylene production process.

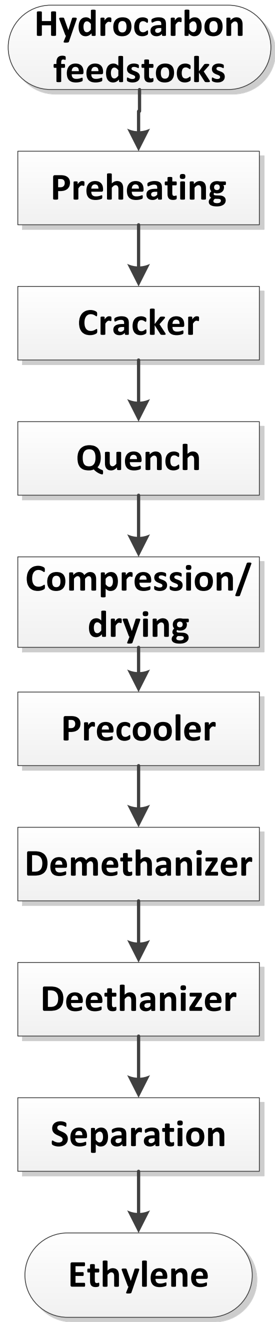

Figure 6-2: Simplified ethylene production process from ethane

The energy intensity of ethylene production from ethane ranges from 17 to 21 GJ/tonne ethylene [399]. Generally, steam cracking of ethane is up to 33% more energy efficient than steam cracking of naphtha [224]. Major energy consumers in the ethylene production process are shown in the demand tree (Figure 6-3).

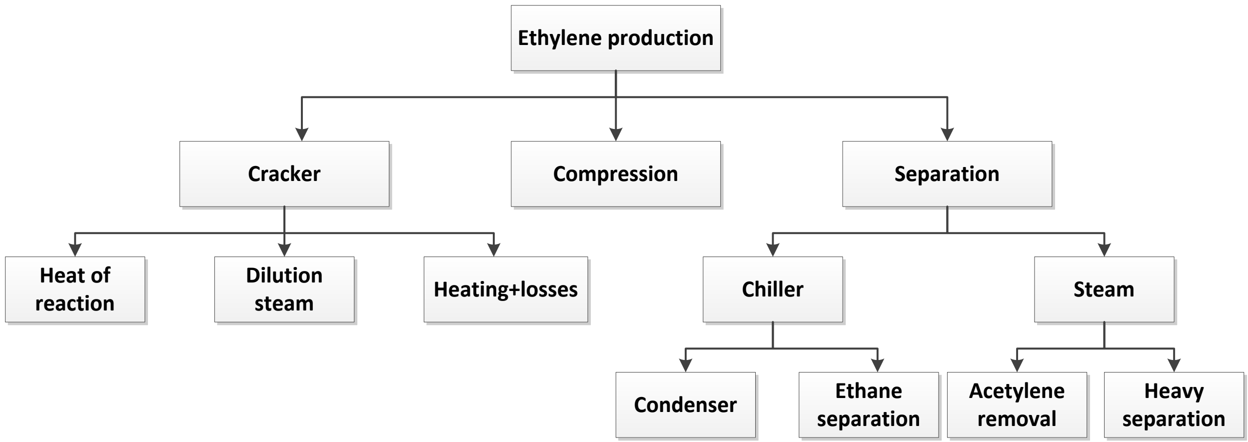

Figure 6-3: Ethylene production demand tree (derived from Worrell et al. [392])

In terms of the type of energy used in each process, while the main energy carrier in the cracker and steam system is natural gas, electricity is used in both the chiller and compression[27] units.

6.4.1.2. Ammonia production

Ammonia is the starting material for the production of all nitrogen-based fertilizers [400]. Ammonia is produced through a reaction between hydrogen and nitrogen. While the main source of nitrogen is the atmosphere, hydrogen comes from a variety of sources including natural gas, water[28], and other hydrocarbons. In Alberta, natural gas is the main feedstock used for ammonia production. Natural gas also serves as the source of energy for providing heat, steam generation, and electricity generation.

Depending on the feedstock used for ammonia production, hydrogen is produced through either steam reforming or partial oxidation. When natural gas is used as the feedstock, steam reforming is the main process for hydrogen production, but when coal is the feedstock, the dominant

[27] Electricity for compressors is generally produced on site.
[28] Hydrogen could be produced from water either through electrolysis of the water or via steam reforming.

process is partial oxidation. In ammonia production in Alberta, where natural gas is the main feedstock, natural gas is both feedstock and energy source. In general, about one-third of GHG emissions are from fuel combustion and the remaining from the use of natural gas as the feedstock in the natural gas-based production route. Figure 6-4 shows a simplified flow of energy in the ammonia production process.

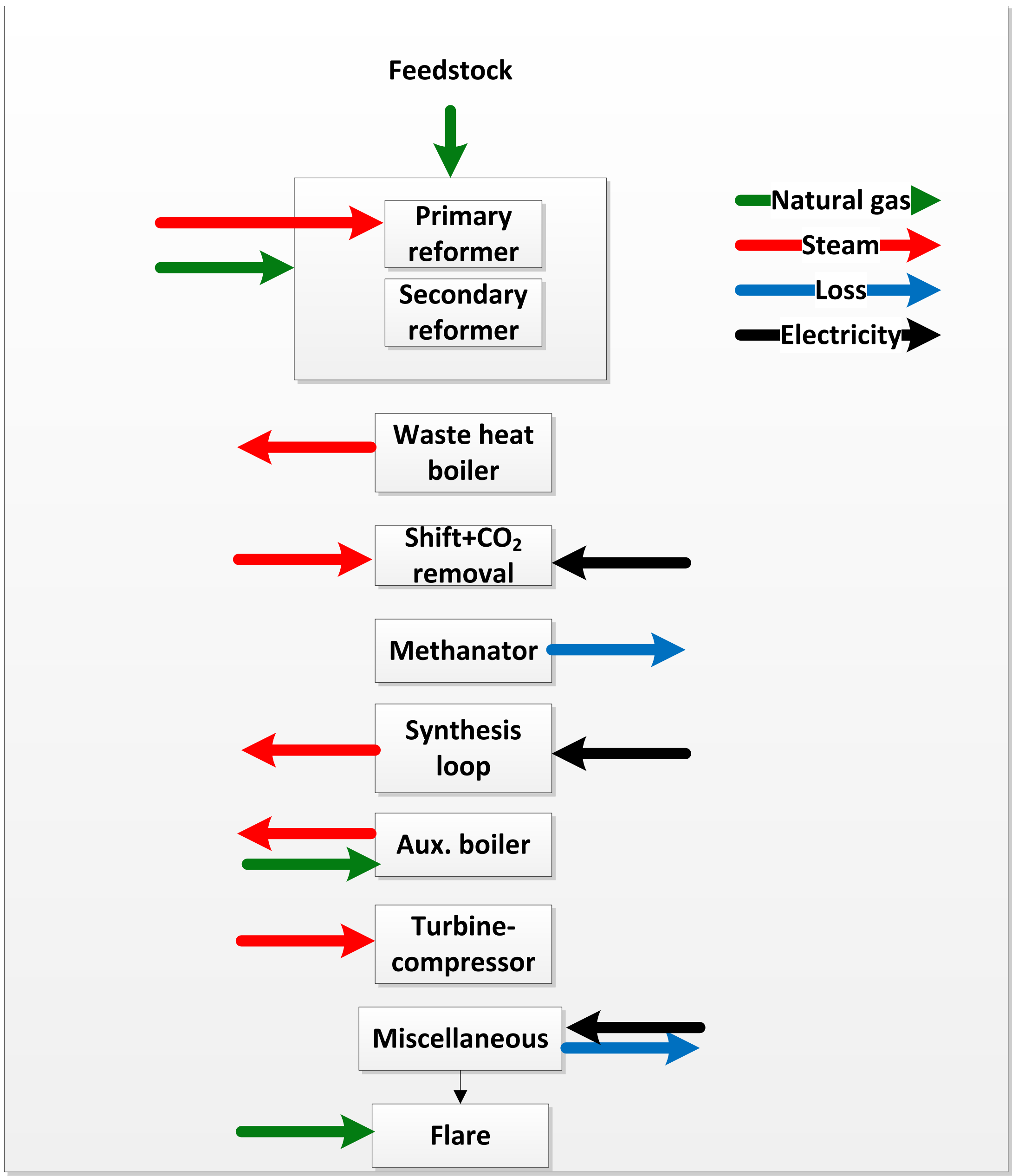

Figure 6-4: Simplified ammonia production process from natural gas

The synthesis of ammonia is the most energy-intensive process in the production of N-fertilizers [401]. The energy intensity of natural gas-based ammonia production plants in Canada ranges from 29.7 to 42.3 with an average of 34.4 GJ/tonne NH_3 [401], and feedstock accounts for more than half the net energy consumption[29] [402]. In modern plants, where the total net energy consumption is around 28 GJ/t, the share of feedstock is almost three-quarters of the total energy consumption [402]. In these plants, even a net steam export is feasible [402, 403]. The ammonia production demand tree is shown in Figure 6-5.

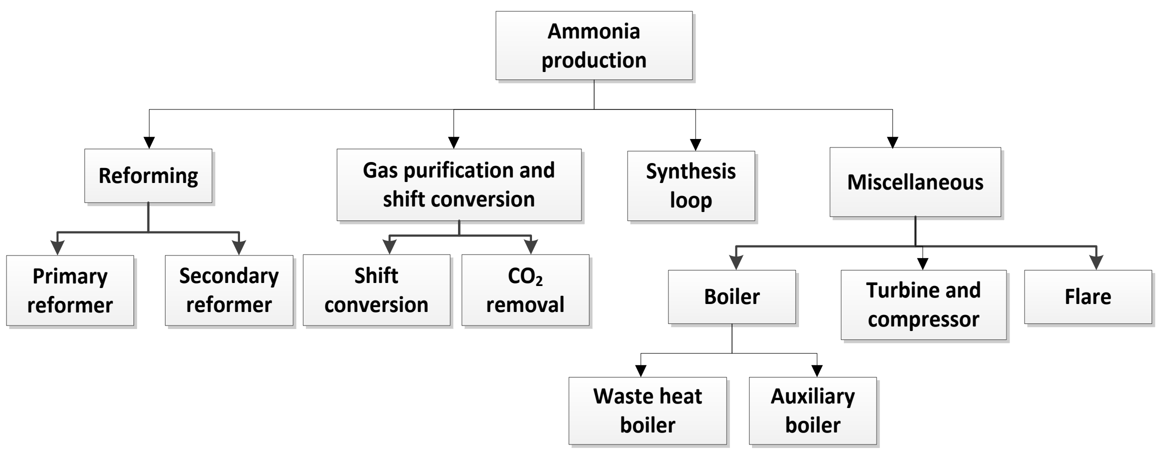

Figure 6-5: Ammonia production demand tree

6.4.2. Base year data collection

The energy model for the province of Alberta was developed as described in earlier studies by Subramanyam and colleagues [404-408]. The data available in different publically available sources, including the Alberta Electric System Operator (AESO), the National Energy Board (NEB), Natural Resources Canada (NRCan), and several other provincial and national databases, were used to populate the model.

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[29] Natural gas is used as both energy source and feedstock. Net energy is an index to report the cumulative consumption of natural gas both as feedstock and as energy carrier.

The model includes various modules in the energy supply, transformation, and demand sectors. For the chemical sector, specific data on production level, energy intensity of different sub-sectors (including equipment-level data), types of energy carriers used in each section, and the emissions associated with each unit were used. The results of the techno-economic model (i.e., the cost of saved energy) were also used as inputs in the LEAP model.

6.4.3. Model verification

The data were validated by comparing the results of LEAP model with the historical data from NRCan (for both energy consumption and GHG emissions). For the verification, two major obstacles were faced, the availability of data on the physical production of petrochemical products [409] and the energy consumption and environmental footprint of different chemical sub-sectors (the publically available data on energy consumption of the chemical industry were aggregated) [234, 410].

To address the first challenge, data for the physical production of ethylene were extracted from the only publically available source, the Canadian Energy Research Institute [411]. In order to assess the share of the petrochemical and fertilizer industries, data on the production level of these two sub-sectors, together with national disaggregated data on energy consumption in the chemical industry [234], were taken into consideration. For GHG emissions, in addition to the above-mentioned sources, Government of Alberta data were considered [412]. The analysis suggests that the two sectors together account for 80% of overall energy consumption and GHG emissions from the provincial chemical sector. This confirms the study's initial assumption that the petrochemical and fertilizer sectors are the main energy consumers and GHG emitters.

We validated the model by comparing the results with actual energy consumption and GHG emissions, as shown in Figure 6-6 and Figure 6-7, respectively.

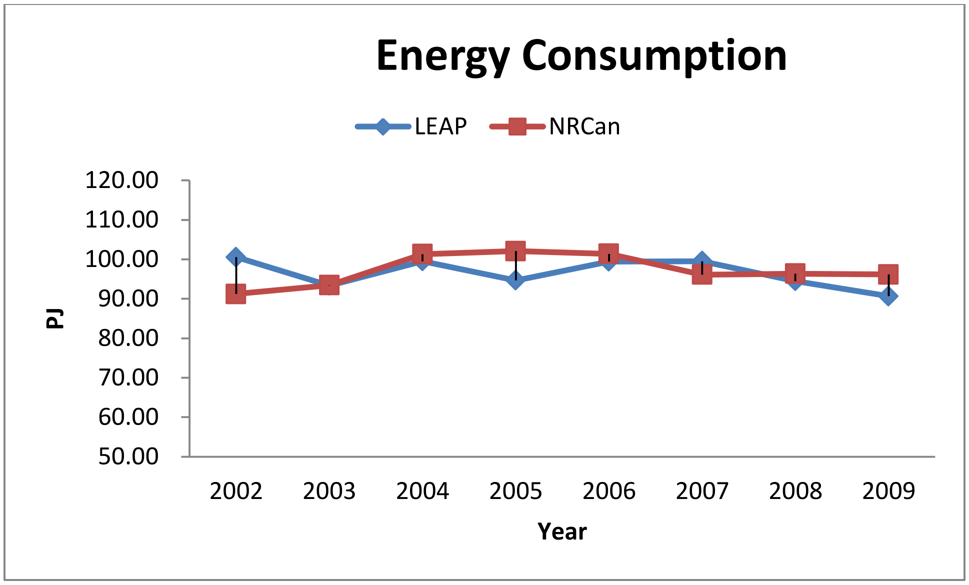


Figure 6-6: Historical energy consumption in the chemical sector

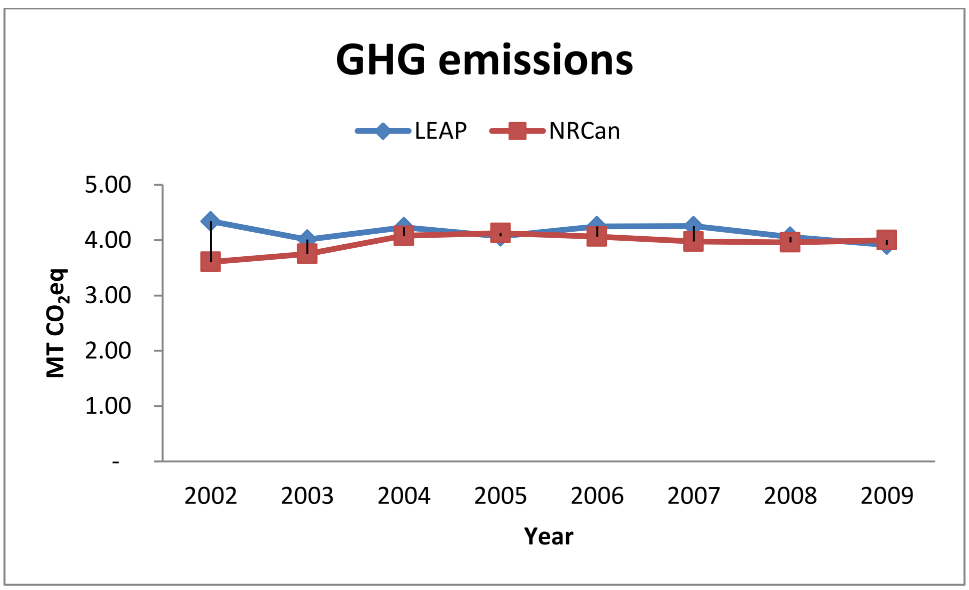


Figure 6-7: Historical GHG emissions in the chemical sector

As shown in Figure 6-6 and Figure 6-7, the results of the LEAP model for both energy consumption and GHG emissions are in line with the data reported in the Natural Resources Canada database [234].

6.4.4. Scenario development

The scenarios were developed using historical production and energy efficiency improvement trends as well as government plans for sector development. The authors consulted industrial experts including representatives from Alberta Innovates – Energy and Environment Solutions (AI-EES).

Scenarios were developed for mid- to long-term time horizons. In the 2030 (mid-term) scenario, it is assumed that the technological changes occur fast and energy efficiency measures would reach their ultimate market shares by 2030. This is in line with the Government of Alberta's Climate Leadership Plan. In the 2050 scenario, a more conservative approach is taken and it is assumed that complete penetration of energy efficiency technologies will take place by the end of 2050.

6.4.4.1. Baseline scenario

In order to predict future energy consumption and GHG emissions in the BAU scenario, a two-step approach was used. The first step was to predict the expansion capacity in Alberta's chemical industry, for which historical production trends and projected development plans for both the petrochemical and the fertilizer sectors were studied in detail[30] and expansion capacity trends from 2016 to 2030/2050 were simulated. In the second step, energy intensity improvement in the sector was predicted with historical data. Further, energy intensity improvement restrictions, which are mainly imposed by the thermodynamic limitations of the processes, were also considered.

- Future production in the petrochemical sector

[30] The recently announced petrochemical diversification program is not considered here as the program is in the early stages of development and its impact on industry expansion cannot be quantified at this stage.

Several factors affect future development of petrochemical industries including feedstock availability, overall production costs, and the sectoral market dynamic [411]. The historical and future perspectives of these factors are summarized in Table 6-3.

Table 6-3: Factors affecting the development of Alberta's petrochemical sector

Factor	Comments/Remarks
Production costs	Energy costs account for more than 70% of overall production costs of ethylene [413]. The cost of natural gas, the main feedstock used in North America and the Middle East, is significantly lower than naphtha, the main feedstock used in Europe and Asia. Thus Canada, and specifically Alberta, is an attractive location for investment in petrochemical projects. However, the competitiveness of feedstock prices (i.e., Canadian vs American) is a considerable barrier for investment in Alberta's petrochemical industry.
Feedstock availability	Available Ethane for ethylene production is expected to reach 350,000 barrels per day and could provide feedstock for three world-class chemical manufacturing plants [414]. This feedstock is expected to become available through various sources including projects approved under the Government of Alberta's Incremental Ethane Extraction Program, Vantage Pipeline from Saskatchewan and Dakota, and also oil sands upgraders off-gas projects [415].
Market dynamics	Because of low feedstock costs and convenient market access in the Middle East and the Asia Pacific, in recent years major global

Factor	Comments/Remarks
	petrochemical investors have been attracted to that part of the world, where low feedstock costs have increased the economic competitiveness of petrochemical production. In Canada, eastern petrochemical industry hubs (i.e., Quebec and Ontario) have better access to markets in north and central United States and Canada. Alberta's petrochemical products are mainly exported to central and western US and offshore. In terms of recent industry developments, there have been major national petrochemical developments in Alberta (mainly in Fort Saskatchewan and Red Deer).
Capital investment	Economic uncertainty, uncertainty about the treatment of capital expenditures (e.g., reductions in supporting schemes such as the Accelerated Capital Cost Allowance [ACCA]), high cost, and the uncertainty of electricity for industrial use are among the main challenges facing chemical industries. However, improved investment conditions resulted in provincial investments 30% above the 2013 level in 2015 [416]. These were followed by more governmental incentives for further development in the petrochemical sector as well as more support programs that were announced in 2016 [417].

Interactions among the factors listed in Table 6-3 are expected to affect the development rate of the industry. A continuation of the historical development trend, along with government plans for industry development, is taken into account in predicting future capacity. An analysis of historical data shows that ethylene production capacity in Canada has been almost constant between 2002 and 2007 and decreased slightly in 2008. In that year, Petro Mont closed its Montreal ethylene cracker and polyethylene unit 40 (whose main feedstocks were naphtha and gas oil), thus taking offline about 300 kt/yr from Canada's total ethylene capacity as well as associated co-products. However, the decrease in production capacity is compensated for by an increase in existing capacity use (i.e., capacity factor), and actual production has remained almost constant with a fluctuation of less than 10% over the past several years. Therefore, historical production is considered to represent future expansion capacity.

- Future production in the fertilizer industry

In the past few years, the ammonia production capacity in Canada has remained almost constant. However, there are plans for two new ammonia production plants in Quebec and Saskatchewan with capacities of 820 and 750 kt per year, respectively. There are also expansion plans for the Brandon plants in Manitoba and the Agrium Redwater plant in Alberta. For the former, a 15% expansion capacity was announced in 2012. However, expansion plans for the Agrium Redwater plant in Alberta have been suspended, and it is unlikely that the expansion plant will become operational [418]. Therefore, despite the projected increase in ammonia production capacity nationally [418], it is assumed that the production capacity will follow the historical trend in Alberta. That is, it is expected that provincial ammonia production will increase from 2,384 ktonne in 2002 to 2,562 ktonne and 2,755 ktonne in 2030 and 2050, respectively (increases of 7.5% and 15.6% from 2002).

Like the petrochemical sector, there has not been any radical improvement in the energy intensity of ammonia production processes in recent years. This is basically because the process is mature and the Canadian ammonia industry is currently among the most efficient worldwide [401]. Therefore, a continuation of historical energy efficiency trends is assumed in developing the BAU scenario.

6.4.4.2. Alternative scenarios

Several alternative scenarios were developed in order to analyze how the penetration of energy efficient technologies would affect energy consumption and GHG emissions in the chemical sector. The energy demand tree described in Section 6.3 provided the opportunity to apply a bottom-up approach to evaluate these impacts. In the demand tree, energy efficiency technologies in different sub-processes were identified and their impacts on the system's energy consumption were analyzed. A comprehensive literature review, as well as expert judgments, was used to analyze the energy efficiency potential in each sub-process/technology identified for different sub-sectors.

Although the Canadian ammonia industry is among the top performing worldwide, there is room for energy efficiency improvement, largely in individual sub-process performance. All the sub-processes in the demand tree were analyzed in detail, and areas where efficiency could be improved were identified. In addition, general energy efficiency improvement in the ammonia industry was studied, and improvement potential was assessed. For the market penetration of the technologies, where data were available, the technology readiness level was used to estimate the market share of the technology at the end of the study period. For other technologies (where no data were available), the current status of the ammonia industry in Canada and its relative performance compared to other countries were used as decision factors [401, 419].

For the ethylene industry, despite the high energy consumption, little data are available in the public domain on specific energy consumption and applicable measures for energy intensity improvement. Most of the available data are very general and not plant-specific; moreover, these are very high-level regional and national data that are not applicable for a bottom-up industrial energy system analysis. Nonetheless, it needs to be noted that data availability differs depending on the ethylene production route, and there are more specific data available for ethylene production from naphtha than from natural gas [224][31]. These limitations make it difficult to identify energy efficiency measures, assess their applicability to Alberta's ethylene production sector, and analyze the cost and environmental benefits associated with their implementation.

However, to the extent possible, state-of-the-art (SOA) and emerging technologies that could be integrated into existing and new plants were identified. The results of the literature review reveal that due to the long life of a petrochemical plant, the suggested energy efficiency measures for petrochemical industries have not changed in the past several years, and this has been confirmed through expert judgement [322].

Johansson and Nakićenović identify the following process-specific energy efficiency measures: more selective furnace coils, improved transfer line exchangers, secondary transfer line exchanger, increased efficiency cracking furnaces, pre-coupled gas turbine to cracker furnace, higher gasoline fractionator bottom temperature, improved heat recovery quench water, reduced pressure drop in compressor inter-stages, additional expander on de-methanizer, additional re-boilers (cold recuperation), extended heat exchanger surface, optimization steam and power balance, and improved compressors [420]. However, the availability of cost and energy saving

[31]For example, in their study, Ren et al. (2006) identified state-of-the-art technologies that could be used in the ethylene production process using naphtha feedstock. Similarly, Worrell et al. (2007) analyzed different industrial sectors (including ethylene production) and compared the energy intensity of the existing processes with best practices.

data as well as their applicability in the short to mid-term are subject to debate and therefore none of these technologies were considered for scenario development.

Other energy efficiency measures were used to develop long-term GHG mitigation scenarios in the LEAP model in the current study. The scenarios for energy saving and GHG mitigation in Alberta’s chemical sector are shown in Table 6-4.

Table 6-4: GHG mitigation scenarios

Scenario	Description
Scenario 1: Adiabatic pre-reformer	An adiabatic steam pre-reformer reduces energy consumption in the reforming section because its use lowers the reformer duty. The highly active nickel catalyst in the pre-reforming will help partially reform the desulphurized hydrocarbon feed by using waste heat from the convection section of the reformer. The technology is commercially available and it is expected that its market share will reach 90% by the end of the study periods. A linear extrapolation was used to predict the penetration trend during the study periods. Compared to existing technologies, the adiabatic pre-reformer will reduce the energy intensity of the reforming section by 1.03 GJ/tNH3. [280, 402]
Scenario 2: Heat recovery from reformer flue gas	Low quality heat from the reformer flue gas is recovered and used to preheat the combustion air, to produce steam at low pressure, or to preheat the boiler feed water. The technology is commercially available and it is expected that its market share will reach 90% by the end of the study periods. Compared to existing technologies, this technology will reduce the energy intensity of the reforming section by 0.22 GJ/tNH3. [280, 419, 421]
Scenario 3: Low-energy CO2 removal technologies	Conventionally, CO2 is removed from a process using chemical absorption methods with the application of monoethanolamine (MEA) as the solvent. Using physical absorption processes (which use an organic solvent and operate through the partial pressure) lead to less circular loading and therefore reduce utility consumption. In addition, using vacuum flashing and air stripping reduces energy consumption for solution regeneration. The market share of the technology is expected to increase by 24% by the end of the study periods. Compared to existing technologies, this technology will reduce the energy intensity of the process by 5.8 GJ/tNH3 [419]
Scenario 4: Autothermic non-constant pressure methanolizing-methanation process	This process is applicable in the shift conversion and CO2 removal sections. The market share of the technology is expected to increase by 38% at the end of the study periods. Compared to existing technologies, this technology will reduce the energy intensity of the process by 1.13 GJ/tNH3 [419]
Scenario 5: Low-temperature conversion technology	The low temperature shift (LTS) guard reactor will be installed before the LTS convertor, thus lowering CO spillage. This itself will lower the hydrogen consumption and therefore increase the ammonia production. The market share of the technology is expected to increase by 17.5% by the end of the study periods. Compared to existing technologies, this technology will reduce the energy intensity of the process by 0.45 GJ/tNH3 [419]
Scenario 6: Unpowered ammonia recovery technology	The conversion rate in the ammonia synthesis process is between 20 and 30%. The co-products of the process are methane and argon, which could exit the system in the form of purge gas. There is some ammonia in the purge gas that could be recovered to improve overall system efficiency. The market share of the technology is expected to increase by 41% at the end of the study periods. Compared to existing technologies, this technology will reduce the energy intensity of the process by 0.5 GJ/tNH3 [402, 419]
Scenario 7: Automatic control and optimization of ammonia synthesis reactor temperature	Automatic control of temperature in the ammonia synthesis reactor will allow the reactor to operate at the lowest stable operating temperature, which itself will result in optimal reactor performance. The market share of the technology is expected to increase by 43% by the end of the study periods. Compared to existing technologies, this technology will reduce the energy intensity of the process by 0.65 GJ/tNH3 [419].
Scenario 8: Large-scale axial and radial ammonia synthesis tower	Axial and radial ammonia synthesis towers (instead of a conventional axial tower, in which the process gas travels axially through the catalyst bed) will increase process efficiency and decrease the pressure drop in the process. The market share of the technology is expected to increase by 44% by the end of the study periods. Compared to existing technologies, this technology will reduce the energy intensity of the process by 3.3GJ/tNH3

	[419]
Scenario 9: Combined heat and power	The overall efficiency of combined heat and power technology is roughly three times higher than conventional technologies. With a cogeneration efficiency of 88-92%, CHP provides considerable energy efficiency improvement in the chemical industry. The market share of the technology is expected to increase by 38% by the end of the study periods. Compared to existing technologies, the technology will reduce the energy intensity of the process by 2.3GJ/tNH3 [419]
Scenario 10: Evaporative condenser cooling technology	An evaporative condenser eliminates the need for treating and pumping large quantities of water. The demand for fan horsepower is considerably lower than in air-cooled systems. In addition, as these systems can work at lower temperatures, they need less energy input. The market share of the technology is expected to increase by 27% by the end of the study periods. Compared to existing technologies, the technology will reduce the energy intensity of the process by 0.09 GJ/tNH3 [419]
Scenario 11: Synthesis gas molecular sieve dryer and direct synthesis converter feed	Molecular sieves used as dryers will help free the make-up gas steam from water and carbon dioxide before they enter the synthesis reactor. The market share of the technology is expected to increase by 29% by the end of the study periods. Compared to existing technologies, technology will reduce the energy intensity of the process by 0.067GJ/tNH3 [419]
Scenario 12: Energy integration (combined refrigeration)	Refrigeration cogeneration systems generate power along with cooling. The system offers an optimized arrangement of energy and exergy flows that ultimately reduce energy consumption compared to separate power generation and cooling systems. The technology is expected to enter the market in 2025 [224]. An energy saving of 1 GJ/t ethylene is achievable by implementing this technology [402]
Scenario 13: High pressure combustion	Combustion under high pressure is more efficient than in atmospheric pressure. However, it needs more oxygen (more than the stoichiometric amount needed for the combustion). The market share of the technology is expected to increase by 40% by the end of the study periods. Compared to existing technologies, the technology will reduce the energy intensity of the process by 1GJ/t ethylene
Scenario 14: Methanolization-hydrocarbylation purification technology	Methane purification technologies are applicable in the shift conversion and CO2 removal sections. The market share of the technology is expected to increase by 31% by the end of the study periods. Compared to existing technologies, the technology will reduce the energy intensity of the process by 1.06 GJ/tNH3 [419].

6.5. Results

As discussed in Section 6.2, a techno-economic model was developed to calculate the cost of saved energy (CSE) from implementing each energy saving option. The model results (which were used as the input for the LEAP model) are presented in Table 6-5. Differences in the capital costs, technology operation and maintenance costs, and the amount and type of saved energy are the main factors affecting the CSE. The CSE changes over time because of changes in fuel cost and the impacts of discount rates.

Table 6-5: Cost of saved energy (CAD/GJ) by scenario

Scenario	2010-20	2020-30	2030-40	2040-50
Scenario 1: Adiabatic pre-reformer	-2.77	-4.59	-5.17	-5.75
Scenario 2: Heat recovery from reformer flue gas	-8.86	-12.82	-13.88	-14.88
Scenario 3: Low-energy CO_2 removal technologies	-3.54	-5.37	-5.95	-6.53
Scenario 4: Autothermic non-constant pressure methanolizing-methanation process	-3.35	-5.17	-5.75	-6.33
Scenario 5: Low-temperature conversion technology	-1.55	-3.37	-3.95	-4.53
Scenario 6: Unpowered ammonia recovery technology	-4.18	-6.01	-6.59	-7.17
Scenario 7: Automatic control and optimization of ammonia synthesis reactor temperature	-4.18	-6.01	-6.59	-7.17
Scenario 8: Large-scale axial and radial ammonia synthesis tower	-4.67	-6.75	-7.38	-8.01
Scenario 9: Combined heat and power	-3.79	-5.61	-6.19	-6.77
Scenario 10: Evaporative condenser cooling technology	-28.85	-42.21	-45.35	-48.21
Scenario 11: Synthesis gas molecular sieve dryer and direct synthesis converter feed	-3.60	-5.42	-6.00	-6.58
Scenario 12: Energy integration (combined refrigeration)	-2.83	-4.65	-5.23	-5.81
Scenario 13: High pressure combustion	9.48	7.66	7.07	6.49
Scenario 14: Methanolization-hydrocarbylation purification technology	-7.69	-11.47	-12.48	-13.45

The medium- to long-term impacts of different energy efficiency options on overall GHG emissions from the industry were analyzed using the results of the LEAP model. Table 6-6 provides the results of the modelling.

Table 6-6: Results of the LEAP model

Energy-efficiency improvement scenarios	Fast penetration scenario (2010-2030)				Slow penetration scenario (2010-2050)			
	Cumulative energy reduction, PJ & GHG mitigation, Mt compared to reference		Incremental NPV (million $) & GHG abatement cost $/tonne of CO2eq.		Cumulative energy reduction, PJ & GHG mitigation, Mt compared to reference		Incremental NPV in million $ and GHG abatement cost $/tonne of $CO_{2eq.}$	
	Energy	GHG	NPV (m)	$/ tonne	Energy	GHG	NPV (m)	$/ tonne
Scenario 1: Adiabatic pre-reformer	12.2	0.7	269	389	20.5	2.8	864	305
Scenario 2: Heat recovery from reformer flue gas	2.6	0.1	118	801	10.7	0.6	273	451
Scenario 3: Low-energy CO_2 removal technologies	18.4	1.0	-10.5	-10.9	75.2	4.3	-61.5	-14.5
Scenario 4: Autothermic non-constant pressure methanolizing-methanation process	5.6	0.5	6.9	15.1	23.2	1.9	14.2	7.5
Scenario 5: Low temperature conversion technology	2.4	0.1	-10	-80	10	0.5	-20	-39.4
Scenario 6: Unpowered ammonia recovery technology	2.7	1.2	-114.3	-92	11.07	0.3	-40	-132
Scenario 7: Automatic control and optimization of ammonia synthesis reactor temperature	7.9	0.6	-120	-213	32.5	2.3	-346	-150
Scenario 8: Large-scale axial and radial ammonia synthesis tower	13.8	0.8	-71	-85	56	3.4	-208	-61
Scenario 9: Combined heat and power	11.7	0.7	-10	-15	48	2.7	-30	-11
Scenario 10: Evaporative condenser cooling technology	0.32	0.1	22	354	1.3	0.3	125	485
Scenario 11: Synthesis gas molecular sieve dryer and direct synthesis converter feed	2.6	0.2	-7.6	-50.4	10.8	0.6	-23	-37
Scenario 12: Energy integration (combined refrigeration)	47	2.8	-29	-10.4	119	6.7	-81	-12
Scenario 13: High pressure combustion:	1.59	0.4	37	97	6.6	1.2	16	14
Scenario 14: Methanolization-hydrocarbylation purification technology	4.3	0.3	8.6	25	17.7	1.4	29	20

6.5.1. Discussion and policy implication

GHG emission reduction cost curves were developed using the results of the LEAP energy modelling. The cost curves, provides a comprehensive overview about the performance of different energy efficiency options in terms of both GHG mitigation potential and its associated costs. To develop the abatement cost curves, the costs of saved carbon were calculated. In the cost curve, emissions reduction and their associated costs are shown on the horizontal and vertical axes, respectively. In other words, the achievable emissions reduction from implementing each scenario (MT CO_{2eq}) is shown on the horizontal axes and the height of each column shows the costs of GHG mitigation that are associated with that particular measure (CAD/ MT CO_{2eq}). Different bars in the cost curve represent different GHG mitigation scenarios.

The GHG abatement cost is the difference between the cumulative cost associated with implementing the energy efficiency measure and the existing technologies over the lifetime of the study. This difference in cost is further calculated in terms of per unit GHG mitigation potential of the efficient technologies compared to the existing technologies. The overall GHG abatement cost is the incremental cost of the alternative scenario compared to the BAU scenario in per unit GHG mitigated. The mitigation potential is cumulative over the time horizons of the study (i.e., 2030 and 2050 in the fast and slow penetration scenarios, respectively).

The cost of GHG mitigation for each energy saving option and the cumulative GHG mitigation potential of the options are shown in Figure 6-8 and Figure 6-9. In order to develop the cost curves, the results were analyzed in two stages. In the first stage, the different energy efficiency options for the chemical sector were assessed in terms of GHG mitigation and associated GHG abatement costs. In the second stage, maximum GHG mitigation potential through the implementation of the selected GHG mitigation options was assessed.

In the first stage, individual mitigation potential for all the options was analyzed for both the fast and slow penetration scenarios. However, because not all the options can be implemented simultaneously, cost curves were developed to assess practical mitigation potential. More precisely, while general efficiency measures, such as an evaporative condenser and combined heat and power technologies, could be implemented at the same time, the simultaneous implementation of sub-sector-specific measures is not possible. For example, low-energy CO_2 removal technologies and CO_2 removal using methyl diethanolamine (MDEA) as solvent will not occur at the same time, as these technologies are practically identical and the implementation of one would considerably affect the performance of the other. In order to account for this, in the second stage of the analysis, mitigation options in each sub-sector were carefully revisited and only those that could be implemented simultaneously were considered in developing the cost curve.

An assessment of the practical mitigation potential for the fast penetration scenario shows that the emissions mitigation potential for the identified options ranges from 0.1 MT to 1.7 MT CO_2 eq. (Figure 6-8). While the maximum GHG mitigation potential from the chemical sector is calculated to be 7.1 MT CO_{2eq}., the largest emissions reduction is achievable through implementing energy integration measures (scenario 12) (i.e., 1.7 MT CO_{2eq} followed by low-energy CO_2 removal technology (1.0 MT CO_{2eq}.) (Sceanario3). On the other hand, the CO_2 mitigation potential for technologies such as heat recovery from reformer flue gas (scenario 2), low temperature conversion technology (scenario 5), evaporative condenser cooling technology (scenario 10), synthesis gas molecular sieve dryer and direct synthesis converter feed (scenario 11), synthesis gas molecular sieve dryer and direct synthesis converter feed (scenario 13) is only 0.1 MT CO_{2eq}. in the same time period.

The results are in line with an earlier study, where it has been suggested that by the year 2030 the overall GHG mitigation potential in the OECD countries would be limited to 20% and 25% in the ethylene and ammonia industries, respectively [422]. The lower range of GHG mitigation potential in Alberta compared to the OECD average could be justified by the fact that the Canadian ammonia industry is among the most energy efficient industries globally, with an energy intensity of 33.1 GJ/tonne NH3, compared to the global average of 38.6 GJ/tonne NH_3. In addition, ethylene production using natural gas (the main feedstock for ethylene production in Alberta) as feedstock is less energy intensive than using naphtha. Therefore, as the main feedstock for ethylene production in Alberta is natural gas, there would be limited potential for a change (such as using natural gas instead of naphtha) that would increase overall mitigation.

Figure 6-8 shows that almost 75% of emissions reduction options have negative GHG abatement costs. For these options, the achievable cost saving due to reduced energy consumption exceeds the capital investment needed to implement the technology. For the options that have positive GHG abatement costs, their implementation will impose a cost to the system. The GHG mitigation cost for different technologies ranges from -213 CAD/tonne saved carbon to +801 CAD/tonne CO_{2eq}. with an average cost of +8 CAD/tonne CO_{2eq}.

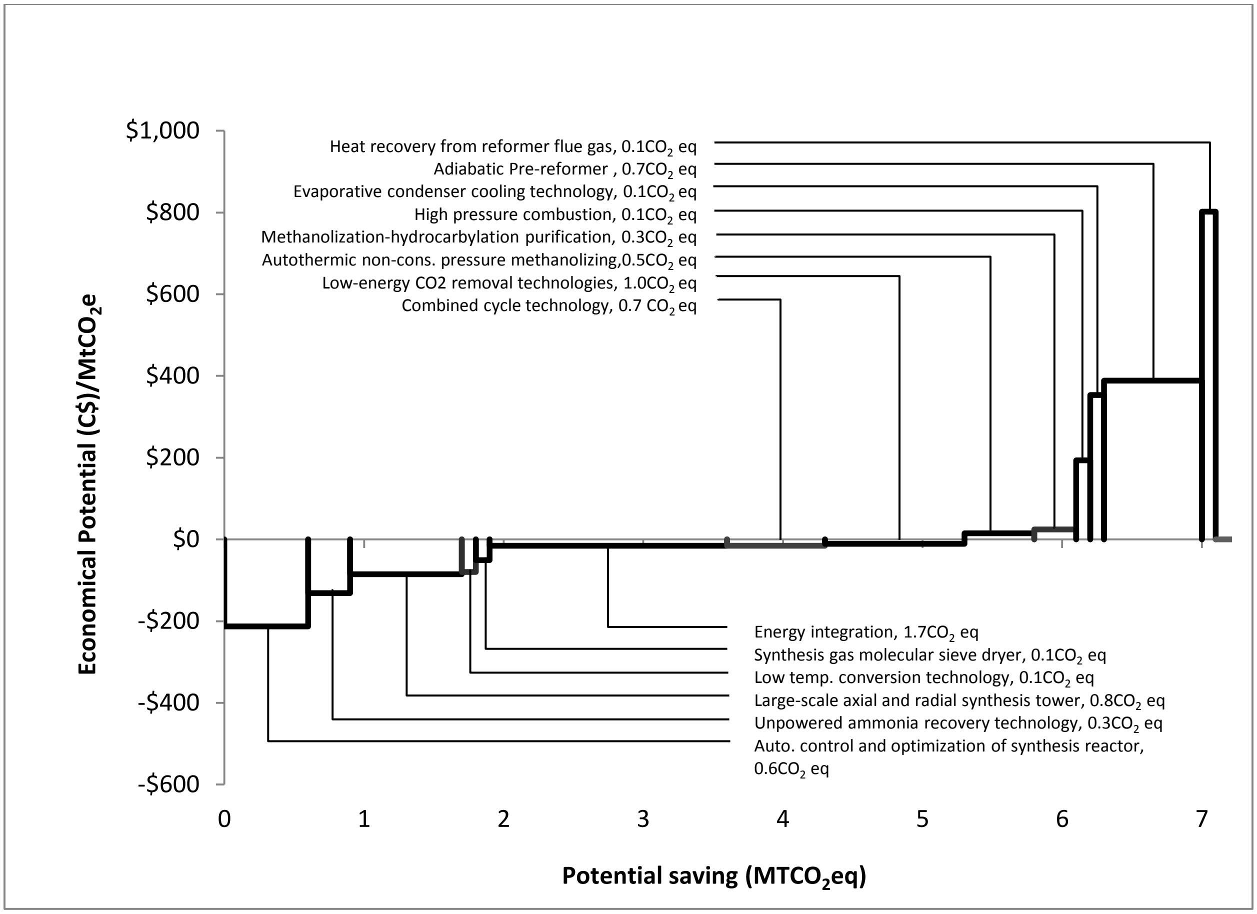


Figure 6-8: Carbon abatement cost curve (fast penetration scenario, 2010-2030)

An analysis was done for the slow penetration scenario and the results are shown in Figure 6-9. The results of the analysis suggest that the cumulative emissions mitigation through the implementation of scenarios with negative GHG mitigation cost is 21.7 MT of CO_2eq. In other words, like fast penetration scenario, almost 75% of the overall mitigation potential (i.e., cumulative mitigation potential of 29.7 MT of CO_2eq.) is achievable with negative GHG mitigation cost.

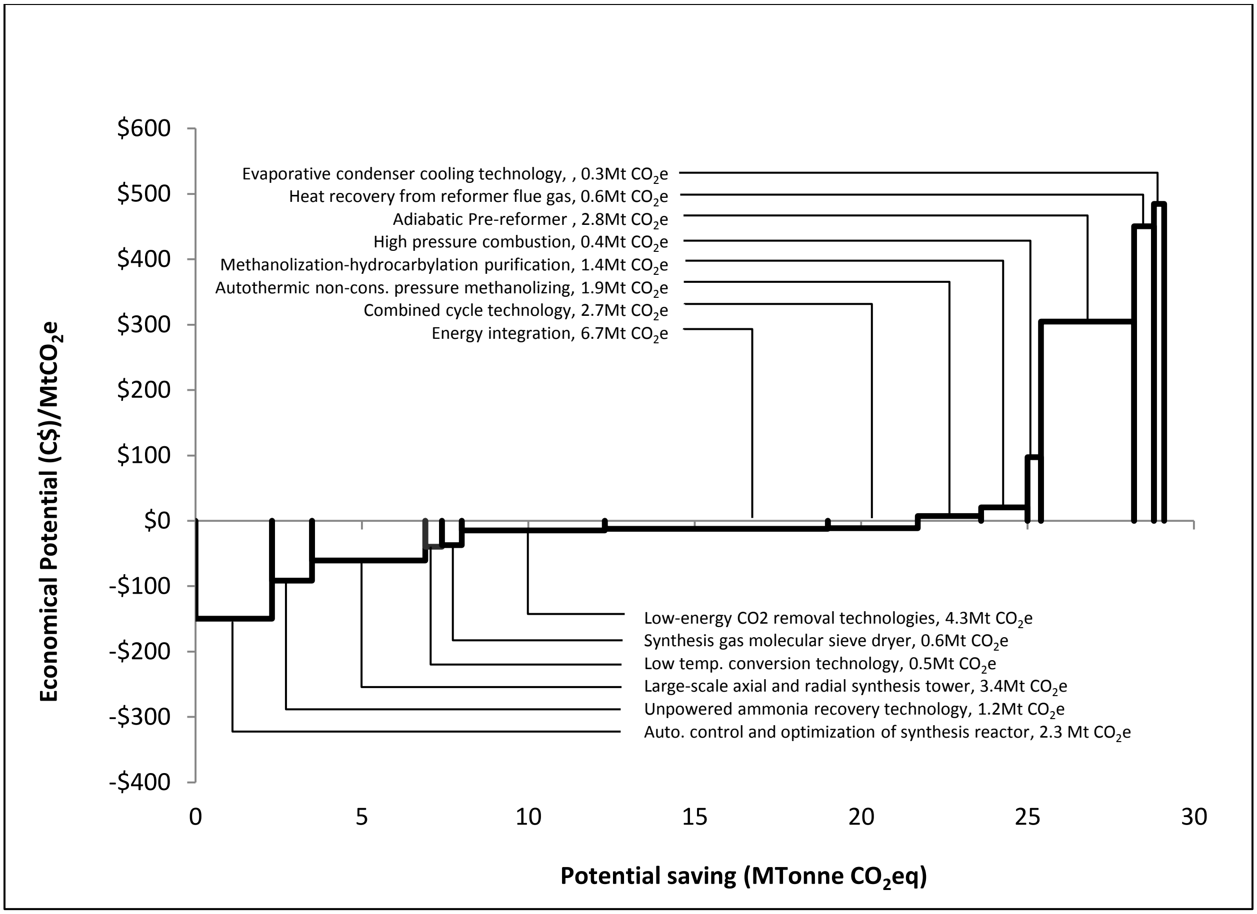


Figure 6-9: Carbon abatement cost curve (slow penetration scenario, 2010-2050)

6.6. Conclusion and future work

In this study, a comprehensive and data intensive framework is developed to analyze the mid- to long-term energy efficiency and GHG mitigation potential in the chemical sector. The proposed framework enables the modeler to analyze the impacts of energy efficiency improvement on GHG emissions from the industrial sector not only at the point of demand (i.e., the chemical production site) but also the life cycle emission occurs as a result of electricity generation and transmission.

The detailed and technology-rich framework is flexible and could be easily transferred in the scientific community to study the long-term the chemical industry different jurisdictions. In addition, given the considerable share of the energy in the overall cost of industry, share of chemical industry in the global GHG emissions and the existing and emerging regulations around carbon emissions at both national and global levels, the results of the analysis are expected to provide invaluable input to both industrial stakeholders and policy makers.

An analysis of both the ammonia and ethylene production industries in Alberta shows that they are more efficient than the world average. In fact, the fertilizers industry in Canada was found to be one of the best performing in the world [401]. The main advantage of Alberta's chemical industry is the use of natural gas (as a low carbon hydrocarbon) as both feedstock and energy carrier.

However, the results of the current study show that there is still potential for energy efficiency improvement and GHG mitigation. In order to assess the long-term energy saving and GHG mitigation potential in the industry, different scenarios were developed in the Long-range Energy Alternative Planning model. The impacts of efficiency measures on overall GHG mitigation potential in the chemical sector were assessed in two different time horizons, up to 2030 and 2050. The results of the modelling suggest that in the chemical sector and compared to the business-as-usual scenario, 7.1 and 29.7 Mtonne CO_{2eq}. can be mitigated by 2030 and 2050, respectively. The results also suggest that for more than two third of the emission reduction, energy efficiency measures would result in economic benefits for the industry and the cost associated with the options is less than the economic benefits achievable from implementing the options.

Chapter 7 : Conclusion and recommendation

7.1. Conclusion

Data analysis and decomposition techniques were used to analyze the historical trends of GHG emissions from the Canadian industrial sector and investigate the contribution of various technical and economic factors. In addition, several industry-specific frameworks were developed to analyze the current status of Canada's manufacturing sector in terms of energy consumption and GHG emissions as well as to identify process-level efficiency options and the sector's system-level energy saving and GHG mitigation potential. The developed framework helps address the gaps and limitations in the existing literature. Long-term GHG mitigation scenarios were developed for four manufacturing industries: cement, iron and steel, petroleum refining and chemical (petrochemical and fertilizers).

The following sub-sections present the key findings from the analysis.

7.1.1. Analysis of historical trends in Canada's industrial greenhouse gas emissions: An index decomposition analysis

In Canada, industrial sector GHG emissions increased by almost 25% between 1990 and 2015. The biggest contributing factor was the increase in activity level in various industrial sub-sectors. The overall economic-energy-intensity of the industrial sector fell by 11% (from 9.3 MJ/$2007 GDP in 1990 to 8.3 MJ/$2007 GDP in 2015). In the 25 years ending in 2015, the energy intensities of the construction, pulp and paper, smelting and refining, petroleum refining and cement industries decreased, while in the mining, forestry, iron and steel and chemical sectors, energy intensity increased. In terms of fuel mix, a shift toward the use of less carbon-intensive fuels between 1990 and 2014 was observed. The emission intensity of Canada's electricity grid fell by 24% in the past 25 years and helped reduce the indirect emissions from in the industrial sector. While industry-specific standards and benchmarks are needed to develop effective energy efficiency regulations, our analysis of historical trends suggests that financial incentives will accelerate the adoption of energy efficiency measures.

7.1.2. **Analysis of the long-term GHG mitigation potential in different industrial sub-sectors**

7.1.2.1. Cement industry

The overall energy and GHG emission intensity of Canada's cement industry decreased by almost 10% in the first decade of this century. In addition to the historical improvement in the industry's emission intensity, there is potential for emissions reduction through process modification, energy efficiency improvement, and the use of alternative materials (as both raw material and fuel source). 20 mid- to long-term emissions reduction scenarios were developed. The cumulative GHG emissions reduction potential from the industry was calculated to be 27.3 $MtCO_2eq$ and 59.9 $MTCO_2eq$ by 2030 and 2050, respectively (Figure 7-1). Using alternative materials as feedstock (i.e., blended cement) was found to have the biggest potential for GHG mitigation (i.e., slightly less than 30% of the overall GHG mitigation potential). Almost 70% of GHG emissions reduction in the sector can be met with negative cost (that is, the financial gains from implementing the option exceed its cost).

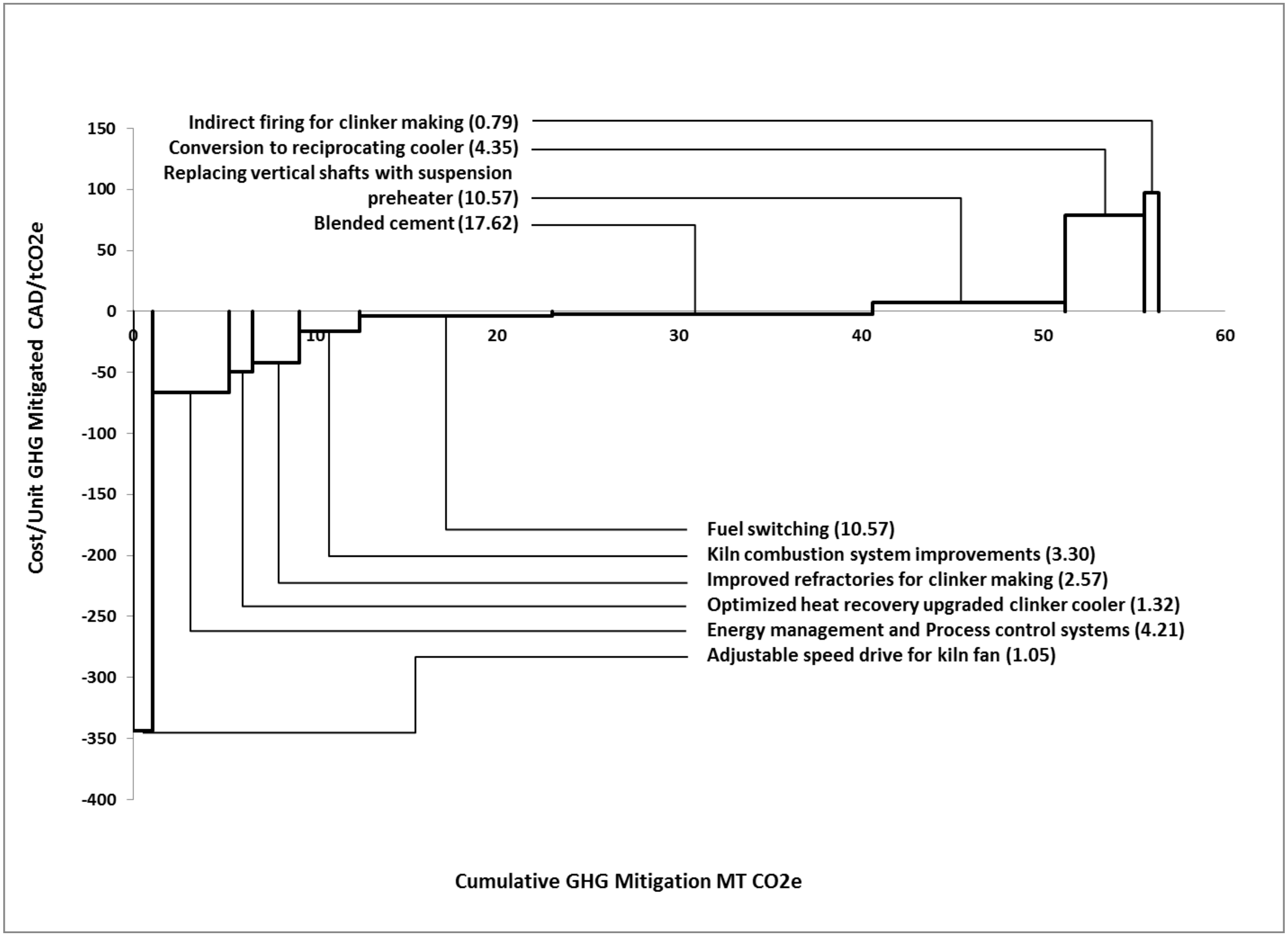


Figure 7-1: GHG mitigation cost curve in Canada's cement sector (slow penetration scenario, 2010-2050)

7.1.2.2. Iron and steel industry

In iron and steel sector, data from a business-as-usual scenario (i.e., continuation of historical trends) suggest that the emissions from Canada's iron and steel industry will grow by 25% by 2030 with no emissions reduction actions. Changes in industry structure and increasing shares of secondary steel production (using scrap steel as feedstock) over primary steel production (using iron ore as feedstock) are expected to reduce iron and steel industry GHG emissions by 11%. Twenty-six applicable energy efficiency options were identified. Their cumulative impact on GHG emissions reduction was calculated to be 5% of the overall BAU emissions. More than 90% of the overall GHG emissions reductions were achievable with negative cost (Figure 7-2).

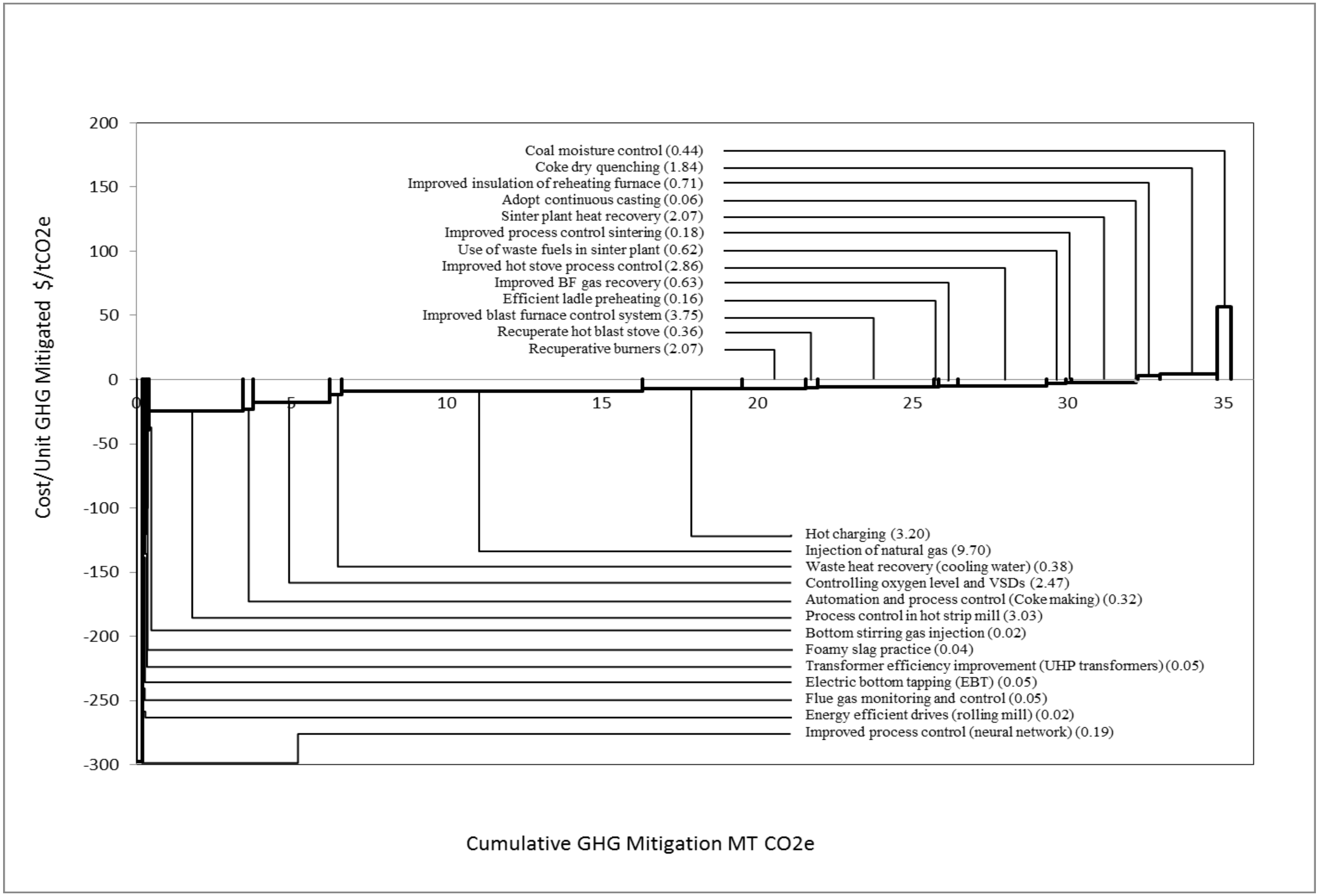


Figure 7-2: GHG mitigation cost curve in Canada's iron and steel sector (slow penetration scenario, 2010-2050)

7.1.2.3. Petroleum refining industry

There are two types of petroleum refineries in Alberta, conventional and oil sands refineries. In terms of process-energy-intensity, the specific energy consumption of oil sands refineries is 17% higher than that of conventional refineries. The energy consumption of the catalytic reforming unit (CRU), the crude distillation unit (CDU), and the fluid catalytic cracking (FCC) can be reduced by 9.54%, 6.39% and 2.38%, respectively, through process heat integration. Air pre-heating is most effective in the CDU unit, where energy intensity can be improved by 17%. In the alkylation and isomerisation units, mechanical heat pumps will reduce energy intensity by 8% and 9%, respectively. Compared to the baseline scenario, using the identified energy efficiency measures cumulatively will reduce the sector's emissions by 5%. Almost 80% of the reduction can be met by implementing energy saving options in the CDU, hydro-treating, alkylation, and isomerization units. In term of economic performance, 60% of emissions can be reduced with negative cost (Figure 7-3).

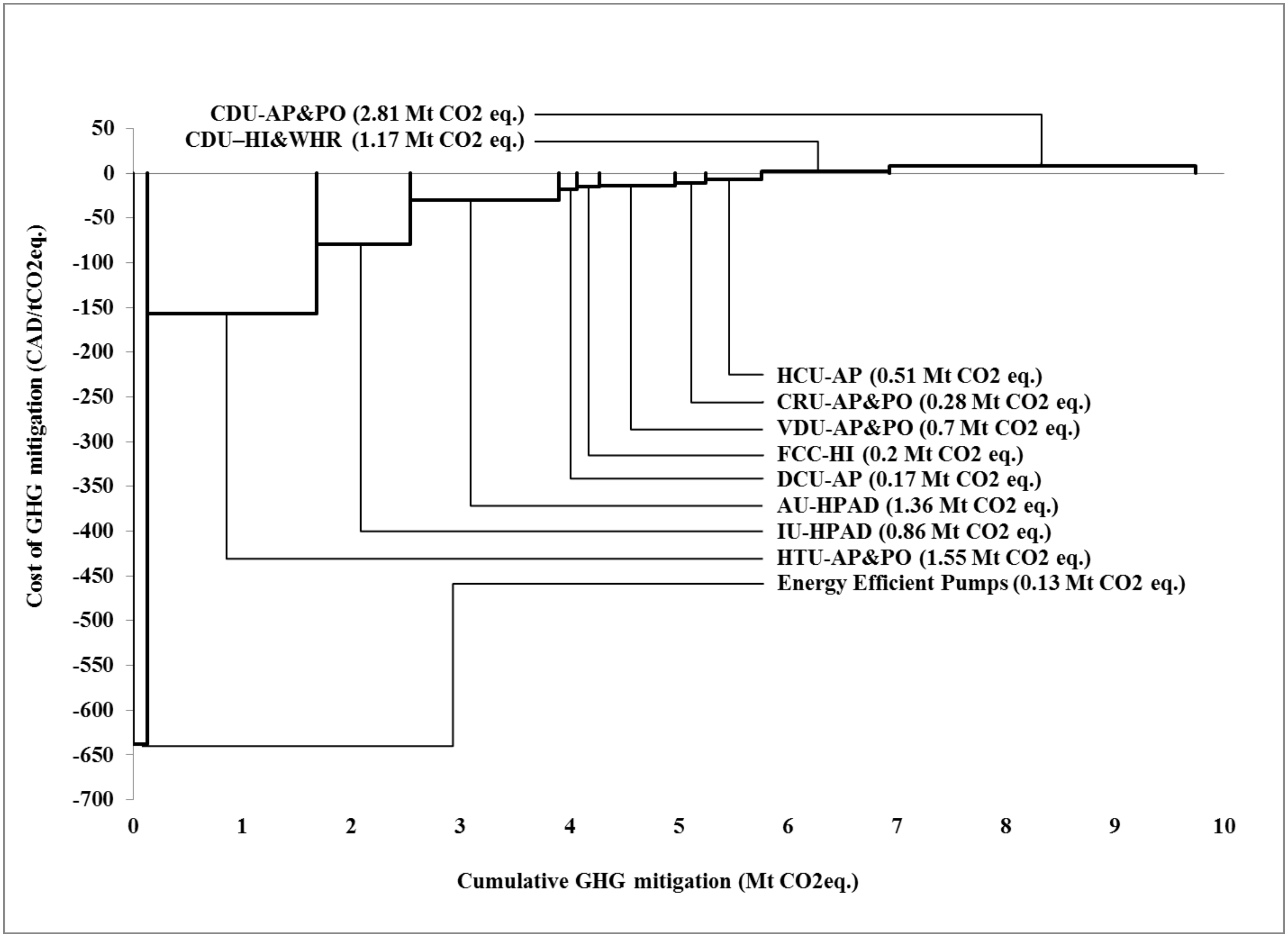


Figure 7-3: GHG mitigation cost curve in Alberta's petroleum refining sector (slow penetration scenario, 2010-2050)

7.1.2.4. Chemical industry

Alberta's chemical sector is among the world's most energy efficient sectors, mainly due to the use of natural gas as feedstock and as a main fuel source (instead of the heavier hydrocarbons used in other parts of the world). Petrochemical and fertilizers industries are the main sub-sectors of the chemical industry in Alberta and cumulatively account for more than 80% of the sector's overall energy consumption and GHG emissions. Twenty-eight GHG mitigation scenarios were developed for the time periods ending 2030 and 2050 (fourteen for each). The overall cumulative emissions reduction potentials were calculated to be 7.1 and 29.7 $MTCO_2eq$ by 2030 and 2050, respectively, more than three-quarters of this achievable with negative cost (Figure 7-4).

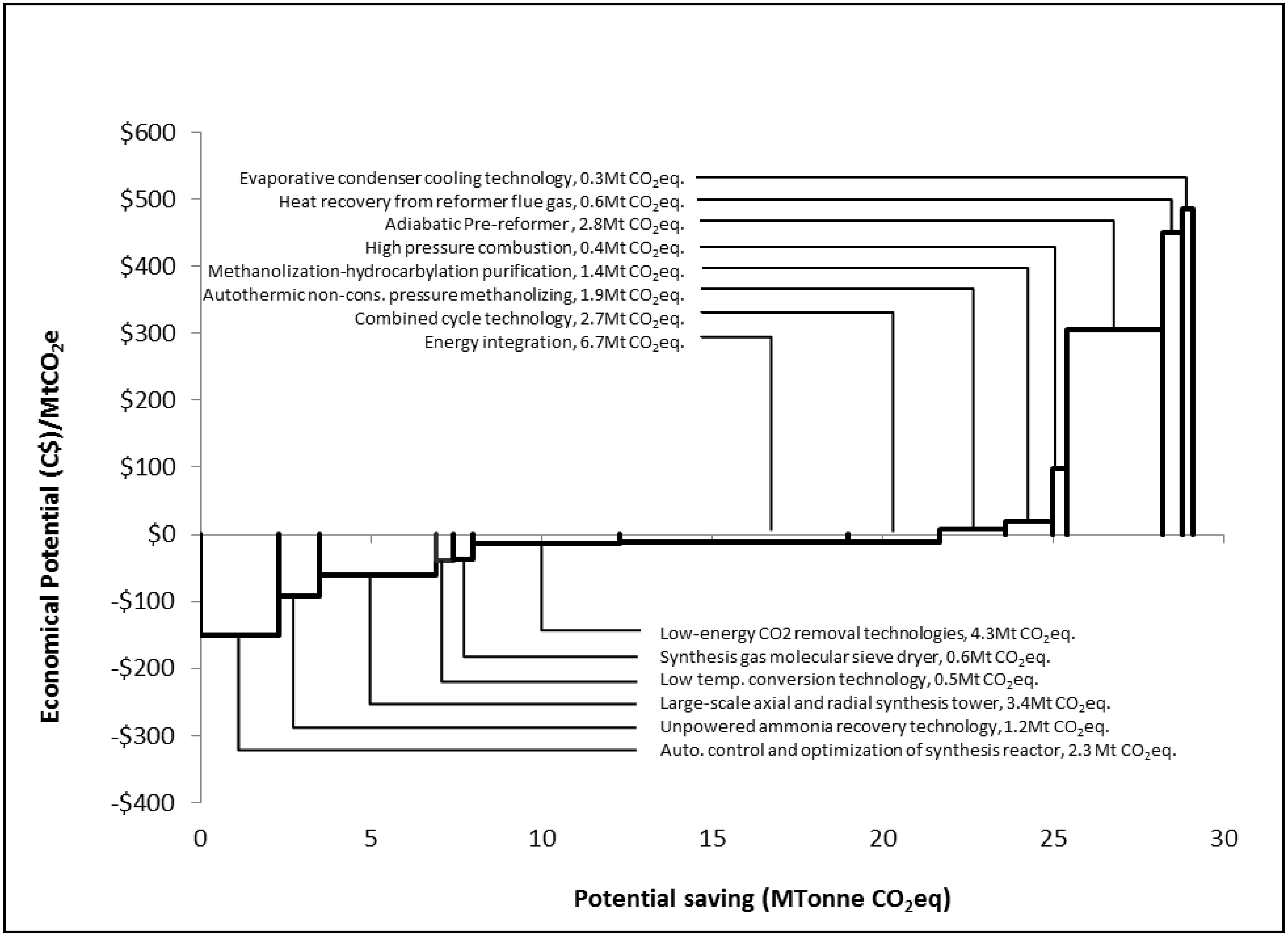


Figure 7-4: GHG mitigation cost curve in Alberta's chemical sector (slow penetration scenario, 2010-2050)

The combined GHG mitigation cost curves for the Canada (cement and iron and steel industries) and Alberta (chemical and petroleum refining industries) are shown in Figure 7-5 and Figure 7-6, respectively. These figures show the relative positioning of different GHG mitigation measures in different industries and can be used in developing industrial climate policy for different industrial sub-sectors.

Comparison of cement and iron and steel industries shows that by 2050, relatively high GHG emissions reduction (59.9 Mt CO_2eq.) is achievable with limited number of GHG mitigation options (10) in the cement industry. In the iron and steel industry the cumulative GHG mitigation option from implementing 26 measures is only 35.3 MT CO_2eq. In terms of GHG abatement cost, while the GHG abatement cost for different options in the cement industry ranges from -343 (CAD/t CO_2eq.) for adjustable speed drive for Kiln production to 97 (CAD/t CO_2eq.) for indirect firing for clinker making, the range is much smaller in the iron and steel industry (i.e., from -297 CAD/t CO_2eq to 57 CAD/t CO_2eq for improved process control-EAF neural network and coal moisture control, respectively).

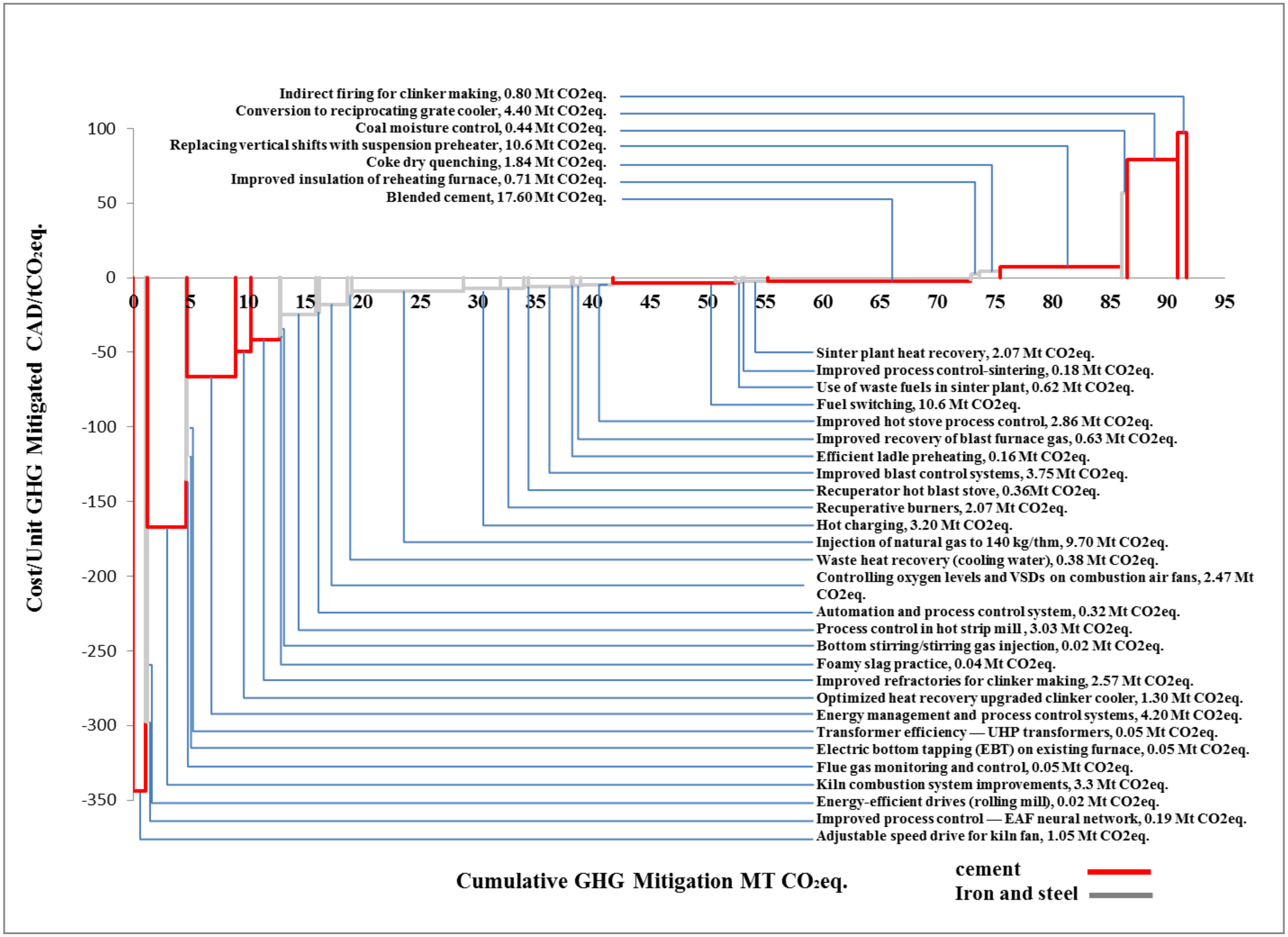


Figure 7-5: Combined GHG mitigation cost curve in Canada's cement and iron and steel industries (slow penetration scenario, 2010-2050)

In Alberta and by 2050, the achievable GHG mitigation potential from chemical (29.7 Mt CO_2eq.) is more than three times higher in the acheviable GHG mitigation from petroleum refining (9.7 Mt CO_2eq.) (Figure 7-6). This is mainly due to the higher share of chemical industry in the overall industrial GHG emissions within the industry (in 2016, chemical and petroleum refining accounted for 11.1% and 4% of the overall GHG emissions from industrial sector, respectively). Compared to the baseline scenario, almost 5% of the emissions can be mitigated in both sectors. On the overall bases, the GHG mitigation from petroleum refining is relatively cheaper compared to that of chemical sector. This is mainly because Alberta's chemical industry is currently among the most efficient industries globally and further improvement in energy efficiency and GHG mitigation requires relatively expensive process modification and industrial retrofits.

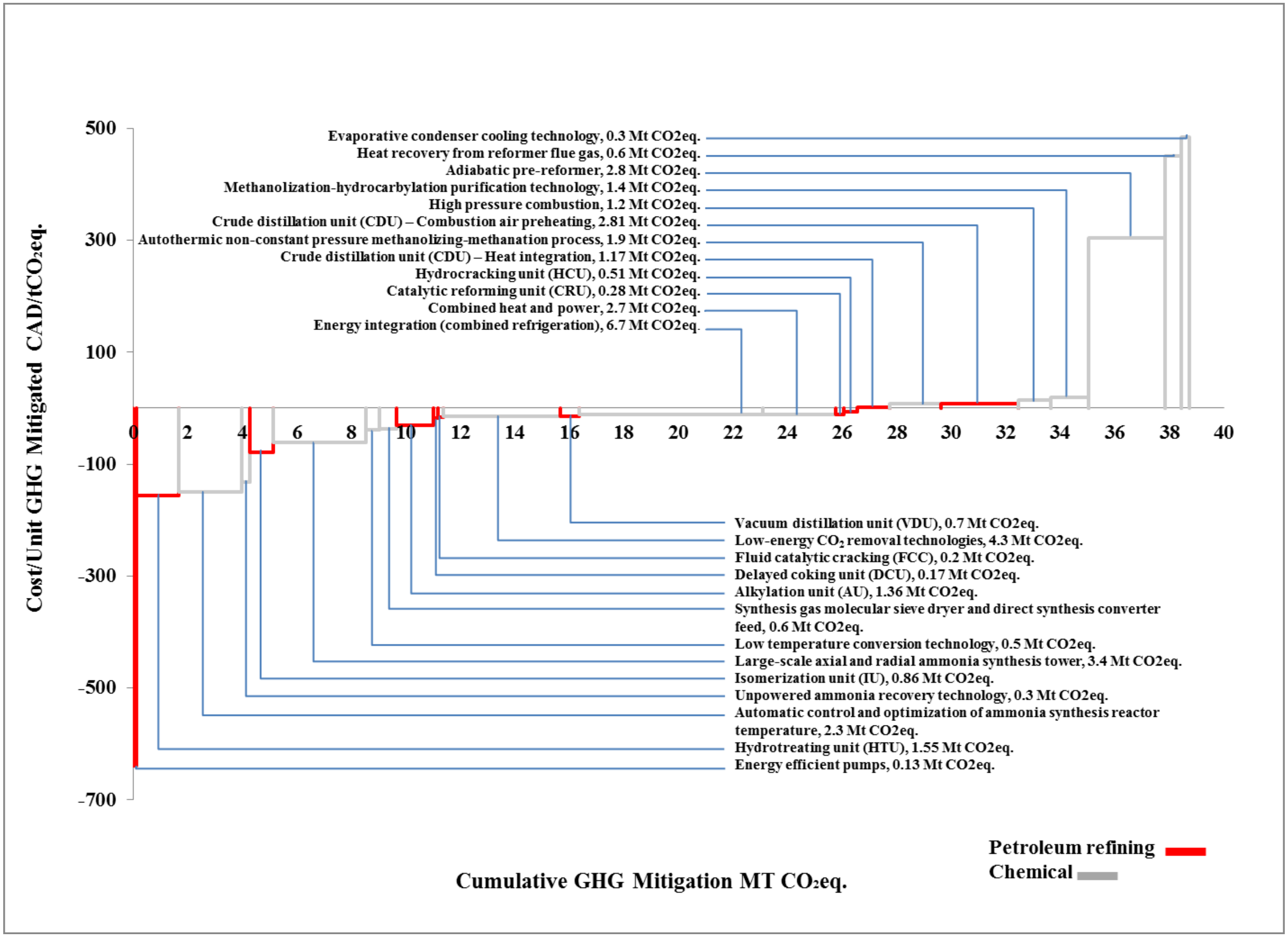


Figure 7-6: Combined GHG mitigation cost curve in Alberta's chemical and petroleum refining industries (slow penetration scenario, 2010-2050)

7.1.3. **Cross sectoral observations**

Historically, energy efficiency has played an alternating role in GHG mitigation from Canada's industrial sector. In terms of both energy consumption ad GHG emissions, Canada's chemical, and iron and steel industries perform better and worse, respectively, than the global average. The historical rates of energy efficiency improvement and GHG mitigation vary from one industry to another. While the energy intensity in petroleum refining has been almost constant, the iron and steel sector has benefited from structural changes and changes in the cement industry have improved its energy efficiency by 10% in less than one decade. In all the studied sectors, there is considerable potential for GHG mitigation through energy efficiency improvement (cumulatively accounting for at least 5% of the overall GHG emissions from the BAU scenario). Most of the GHG mitigation potential can be met with negative cost (i.e., the implementation of the technologies will result in economic gains). Therefore, energy efficiency improvement is often considered the low hanging fruit when it comes to decarbonizing the industrial sector.

7.2. Contribution and implication for policy

The contribution of the current research is twofold. First, the sub-sectoral frameworks presented in this thesis are comprehensive, technologically rich, and flexible. These make the frameworks easily transferable, and the models can be used by academics and policy makers to study long-term industrial energy efficiency and GHG mitigation potential in other jurisdictions. For each sector, we developed energy consumption demand trees, which provide invaluable insights on the process energy intensity as well as the type of fuel used in each process. These data are transferable and can be used to develop identical energy models for the industrial sector in other jurisdictions. Also, the different cost components used in the analysis allow the user to account for technology-specific costs (i.e., capital and operation and maintenance cost) as well as macro-economic factors (such as fuel cost and carbon cost) in the analysis.

In the developed framework, the user can consider the carbon cost as an external cost or include it as a component of the operational cost. We assessed the performance of a carbon pricing scheme in Canada using the former approach and identified areas of improvement for the existing pricing scheme that could help the scheme reach the maximum mitigation potential. Using this approach also allowed us to consider different carbon cost scenarios and assess the sensitivity of the findings to the changes in the price of carbon.

Second, this study addresses the gaps in knowledge in Canada's industrial climate policy. By developing fact-based scenarios, the work quantifies the long-term achievable GHG emissions from Canada's manufacturing industries.

The results of the analysis provide invaluable input to policy makers on the long-term potential for sectoral GHG mitigation, its associated cost, and specific areas of energy efficiency improvements to be considered when developing regional and national climate policies. In addition, with the existing and emerging environmental regulations in the carbon-constrained world, the results of this study can be effectively used by industrial stakeholders for their future investment and development decisions.

7.3. Recommendations for future work

The following recommendations for future work were identified from this research study:

7.3.1. Alternative and emerging GHG mitigation technologies

This study analyzed energy efficiency improvements and their impacts on GHG mitigation from Canada's manufacturing industries. In order to evaluate the ultimate GHG mitigation potential from these sectors, in addition to energy efficiency, it is crucial to assess the applicability of emerging technologies such as carbon capture, utilization, and storage and their impact on sectoral GHG mitigation potential. Techniques such as geographical information system (GIS) analysis can be used to link emissions sources and sinks and evaluate the technical feasibility of the technology in different jurisdictions.

The potential for industry to adopt renewable energies (i.e., decentralized electricity production), energy storage potential, and the impacts of adopting them on overall industrial GHG emissions can also be the subject of future studies. The share of electricity in Canada's industrial fuel mix has increased over time. This trend is expected to continue, and therefore it would be beneficial to assess potential future trends of industrial electrification and its impacts on sectoral GHG emissions.

7.3.2. **Other environmental impacts**

The current research analyzed the long-term GHG mitigation potential in Canada's manufacturing industries. The impacts of modifications on the emissions of other air pollutants and on water consumption were not analyzed and could be considered in future studies.

7.3.3. **Policy analysis**

From the climate policy perspective, there are two ways in which the current study can be expanded. The first uses the implications of the findings for long-term climate change policy making. For example, we investigated the limitations of current climate policies in the petroleum refining sector and, based on the results of the current research, proposed some modifications to improve the performance of the industrial carbon pricing system in Alberta. Similar work can be done for other industrial sub-sectors. Second, the effectiveness of climate policies on promoting energy efficiency in the industrial sector needs to be analyzed. It is important to develop policies that will promote energy efficiency in the sector. Such policies will help realize the areas of GHG mitigation potential identified in this thesis.

Appendix

Appendix I-Supplementary information for Chapter 2

Appendix I-I: Model for decomposition analysis

```
clear all

close all

clc

for t=1:25

   E=xlsread('C:\Users\kheradma\Desktop\alireza\New Folder\2018-01-18 E-Decompostion Energy raw data.xlsx',t);

   C[423][423][423]=xlsread('C:\Users\kheradma\Desktop\alireza\New Folder\2018-01-07-C-Decompostion Emissions raw data.xlsx',t);

   Q(:,t)=xlsread('C:\Users\kheradma\Desktop\alireza\New Folder\2018-02-15-Q-Decomposition GDP raw data.xlsx',t);

   I(:,t)=xlsread('C:\Users\kheradma\Desktop\alireza\New Folder\2018-02-15-EtoQ-Decomposition Energy intensity raw data (MJper2007gdp).xlsx',t);

   UR(:,t)=xlsread('C:\Users\kheradma\Desktop\alireza\New Folder\2018-01-07-U Capacity Utilization Rate (%).xlsx',t);

end

for t=1:25

   SE=E[423][423][423];

   SC=C[423][423][423];

   SC=SC([3 4 8 1 2 6 5 7 9 10],[2 4 6 9 7 8 5 3 1 10]);

   for i=1:10

      for j=1:10

         if isnan(SE(j,i))

            SE(j,i)=0;

         end

         if isnan(SC(j,i))
```

```
            SC(j,i)=0;
        end
        if SE(j,i)==0
            SE(j,i)=.002;
        end
        if SC(j,i)==0
            SC(j,i)=.002;
        end
    end
end
E[423][423][423]=SE;
C[423][423][423]=SC;
end
SC0=C[423][423][423];
SE0=E[423][423][423];
for t=1:25
    SC=C[423][423][423];
    SE=E[423][423][423];
    DP=0;DM=zeros(1,10);DE=zeros(1,10);
    for i=1:10
        ms=0;
        mI=0;
        mU=0;
        for j=1:10
            L=(SC(j,i)-SC0(j,i))/(log(SC(j,i)/SC0(j,i)));
            if isnan(L)
                L=SC(j,i);
```

```
            end
            DP=DP+L;
            ms=ms+L;
            mI=mI+L;
            mU=mU+L;
            M(j,i)=SE(j,i)/(sum(SE(:,i)));
            U(j,i)=SC(j,i)/SE(j,i);
            M0(j,i)=SE0(j,i)/(sum(SE0(:,i)));
            U0(j,i)=SC0(j,i)/SE0(j,i);
            DM(i)=DM(i)+L*log(M(j,i)/M0(j,i));
            DE(i)=DE(i)+L*log(U(j,i)/U0(j,i));
        end
        DS(i)=ms*log(Q(i,t)*sum(Q(:,1))/Q(i,1)/sum(Q(:,t)));
        DI(i)=mI*log(I(i,t)/I(i,1));
        DU(i)=mU*log(UR(i,t)/UR(i,1));
    end
    DP=DP*log(sum(Q(:,t))/sum(Q(:,1)));
    production(t)=DP;
    structure(t)=sum(DS);
    intensity(t)=sum(DI);
    utlization(t)=sum(DU);
    Fuelmix(t)=sum(DM);
    emission(t)=sum(DE);
end
for k=1:25
    total(k)=production(k)+structure(k)+intensity(k)+utlization(k)+Fuelmix(k)+emission(k);
end
```

Appendix I-II: Input data for the decomposition analysis

Table A-1: Historical Energy consumption in Canada's industrial sector-Energy use by industry (PJ)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Total	2710	2675	2686	2704	2855	3017	3020	3086	2999	3046	3167	3023	3140	3203	3367	3306	3307	3435	3294	3136	3237	3321	3416	3525	3584
Construction	67	58	58	51	54	49	50	49	48	51	51	51	58	63	68	71	72	75	75	66	73	79	82	79	76
Pulp & Paper	728	496	488	491	516	833	806	845	796	851	868	794	827	816	902	827	750	724	633	579	553	541	525	560	576
Smelting & Refining	183	188	198	211	223	219	230	229	237	235	231	246	251	256	248	261	263	256	261	228	240	249	230	225	229
Petroleum Refining	323	320	324	323	311	356	350	357	351	275	338	355	381	363	397	357	371	380	347	339	344	339	343	321	319
Cement	59	51	51	51	59	62	59	59	61	63	67	64	68	68	70	71	76	67	65	62	60	58	57	55	57
Chemicals	223	233	222	211	242	248	252	262	262	265	260	230	231	214	244	236	248	243	242	231	249	272	272	285	292
Iron & Steel	219	235	245	242	250	247	251	253	256	261	260	229	247	241	250	240	252	254	247	187	213	227	231	215	231
Other Manufacturing	551	756	752	706	772	550	541	551	523	532	564	515	523	525	542	547	532	542	522	479	472	489	501	522	508
Forestry	8	7	7	8	8	8	10	11	12	15	17	20	20	23	28	29	31	30	31	21	22	20	19	19	18
Mining	348	332	341	411	419	446	469	471	451	498	510	518	535	634	619	667	712	863	872	943	1011	1048	1156	1244	1276

Table A-2: Historical Energy consumption in Canada's industrial sector-Energy use by energy source (PJ)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Total Energy Use (PJ)	2710	2675	2686	2704	2855	3017	3020	3086	2999	3046	3167	3023	3140	3203	3367	3306	3307	3435	3294	3136	3237	3321	3416	3525	3584
Electricity	658	668	673	695	713	733	738	748	757	771	796	793	801	804	804	842	834	819	794	721	730	730	721	723	721
Natural Gas	837	821	825	825	866	910	937	971	910	920	961	835	917	927	934	904	896	1036	1037	1007	1111	1185	1293	1428	1476
Diesel Fuel Oil, Light Fuel Oil and Kerosene	128	119	108	115	128	115	130	133	130	131	141	138	133	145	159	170	173	186	190	175	211	226	221	222	208
Heavy Fuel Oil	201	179	161	162	160	147	156	155	148	139	143	144	125	150	156	134	119	120	101	90	60	45	44	42	40
Still Gas and Petroleum Coke	310	303	334	342	348	412	395	390	387	370	376	415	438	438	481	470	509	526	474	513	501	500	498	477	468
LPG and Gas Plant NGL	26	28	32	33	28	32	29	31	32	30	39	41	36	32	34	46	49	52	55	51	60	65	78	67	63
Coal	49	43	42	40	44	47	47	48	48	52	58	61	54	58	59	53	57	57	57	48	54	56	54	47	44
Coke and Coke Oven Gas	131	145	143	136	135	134	135	133	131	135	137	129	127	127	125	126	135	126	126	98	110	120	120	99	103
Wood Waste and Pulping Liquor	341	337	344	338	408	458	425	452	426	463	479	430	470	476	573	523	499	477	427	394	375	364	356	391	423
Other	28	31	24	19	27	30	29	25	31	35	37	37	39	45	42	38	38	35	33	41	25	30	31	30	37

Table A-3: Historical GHG emissions in Canada's industrial sector (including electricity)-GHG emissions by industry (Million tonne of CO_2eq.)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Total	141	138	140	138	140	148	149	155	156	153	160	159	161	168	170	167	167	178	170	158	169	169	175	179	178
Construction	4.3	3.7	3.7	3.3	3.5	3.2	3.3	3.2	3.2	3.3	3.4	3.4	3.8	4.1	4.5	4.7	4.8	5.0	5.0	4.5	4.9	5.3	5.5	5.4	5.1
Pulp & Paper	24.5	23.5	22.8	21.9	21.8	22.5	22.5	24.0	24.3	24.1	24.9	23.9	23.3	23.5	22.8	20.0	17.5	17.3	14.3	12.4	11.9	10.9	9.8	10.4	9.9
Smelting & Refining	10.9	10.9	11.8	11.4	11.9	11.9	12.2	12.9	14.6	13.5	13.6	15.3	15.2	16.2	15.0	15.1	14.9	14.7	14.3	11.5	12.5	11.7	10.3	10.1	9.5
Petroleum Refining	18.2	18.2	18.4	18.5	17.6	20.7	20.3	20.7	20.4	16.2	19.3	20.3	21.1	20.3	23.6	20.9	21.1	21.7	19.2	18.8	19.8	19.1	20.3	19.1	18.9
Cement	4.4	3.9	3.9	3.9	4.5	4.7	4.6	4.5	4.6	4.8	5.2	5.1	5.3	5.6	5.8	5.8	6.2	5.5	5.3	5.0	4.8	4.7	4.3	4.1	4.3
Chemicals	10.9	10.9	10.9	10.3	11.6	11.9	12.2	13.3	13.8	13.7	13.5	12.1	11.9	11.3	12.6	12.0	12.4	12.2	11.9	10.9	11.9	12.6	12.4	12.9	13.0
Iron & Steel	16.5	18.0	18.7	18.2	18.0	18.2	18.3	18.4	18.9	19.1	19.2	17.3	18.1	17.8	18.3	17.4	18.6	18.8	18.1	13.6	15.6	16.5	16.6	14.7	15.8
Other Manufacturing	28.7	27.2	27.2	24.3	24.8	26.6	25.9	27.0	25.9	25.5	27.3	26.3	26.0	26.0	25.8	26.3	24.5	25.4	23.7	20.5	21.5	21.2	21.3	21.7	19.5
Forestry	0.6	0.5	0.5	0.6	0.6	0.6	0.7	0.8	0.9	1.1	1.3	1.5	1.5	1.7	2.1	2.1	2.3	2.2	2.3	1.6	1.6	1.5	1.4	1.4	1.4
Mining	22.5	21.2	21.6	25.5	26.0	27.7	29.2	30.1	29.5	31.3	32.8	33.5	34.5	41.3	40.1	42.2	45.0	55.1	55.6	59.6	64.5	66.0	73.3	79.2	80.5

Table A-4: Historical GHG emissions in Canada's industrial sector (including electricity)-GHG emissions by energy source (Million tonne of CO_2eq.)

Total	141	138	140	138	140	148	149	155	156	153	160	159	161	168	170	167	167	178	170	158	169	169	175	179	178	178
Electricity	37	36	38	35	35	37	36	40	46	43	46	49	48	50	48	47	45	45	41	34	36	31	29	29	27	26
Natural Gas	44	42	43	43	44	47	49	51	47	48	51	44	49	51	51	49	49	59	59	57	64	68	74	82	85	87
Diesel Fuel Oil, Light Fuel Oil and Kerosene	9	9	8	8	9	8	9	10	10	10	10	10	10	11	12	13	13	14	14	13	16	17	16	17	15	16
Heavy Fuel Oil	15	14	12	12	12	11	12	12	11	10	11	11	9	11	12	10	9	9	8	7	5	3	3	3	3	2
Still Gas and Petroleum Coke	18	17	19	20	20	24	23	23	23	22	22	24	25	25	29	28	30	31	27	30	30	29	31	30	29	30
LPG and Gas Plant NGL	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	3	3	3	3	3	4	4	5	4	4	4
Coal	5	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	4	5	5	5	4	4	4
Coke and Coke Oven Gas	12	14	14	13	13	13	13	13	13	13	13	12	12	12	12	12	13	12	12	9	10	11	11	9	10	9
Wood Waste and Pulping Liquor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0

Table A-5: Historical activity level in Canada's industrial sector-Activity level by industry (GDP (million CAD 2007))

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Construction	72696	66953	62007	59814	61639	59346	61464	64885	66935	70058	73707	79042	82439	85194	90086	94414	98021	102098	104738	98211	105559	109208	117567	122475	125632
Pulp and paper	8313	7885	8103	8698	9142	9048	9204	9256	9015	9832	10316	9836	10301	10317	10409	10435	9375	9304	8615	7029	7606	7328	6932	6662	6985
Smelting and refining	3921	3818	3514	3282	4367	4855	4847	5658	6317	6727	7662	8453	8302	8027	9039	9504	9357	8963	8888	7245	7579	8101	7841	7389	8142
Petroleum refining	5712	5438	5615	5639	5812	5792	5911	6260	6621	6222	5954	6782	6598	6759	6677	6408	6045	6147	6007	6320	5947	5617	5800	5862	6083
Cement	699	519	486	492	527	541	643	894	849	836	897	950	936	952	1064	1236	1253	1217	1112	933	914	932	900	900	1006
Chemicals	2826	2552	2571	2618	2753	3013	3073	3552	3515	3502	3724	3367	3216	3548	3439	3643	3771	3540	3135	2436	2859	3131	2997	3132	2901
Iron and steel	2592	2315	2477	2939	3328	3932	3503	3806	4079	4087	4262	3588	4152	3910	3892	3807	3790	3809	3298	2018	2728	3033	3095	2927	3063
Other manufacturing	105268	97688	99260	105045	112471	118156	119752	127248	134113	146497	164977	156058	157174	155506	158097	160802	159339	154812	146316	126583	131963	137013	140228	139790	144056
Forestry	5974	5255	5387	5600	5849	6064	5648	5213	5358	5626	5914	5924	6056	5977	6315	6402	6147	5730	5352	4509	5037	5451	5339	5531	5287
Mining	83399	87018	89590	93432	97523	100998	102078	104551	106114	105916	109262	109383	112005	115182	117133	118407	121751	123107	120337	108382	115085	123319	120726	126482	135841

Appendix II: Supplementary information for Chapter 3

Appendix II-I: Model verification

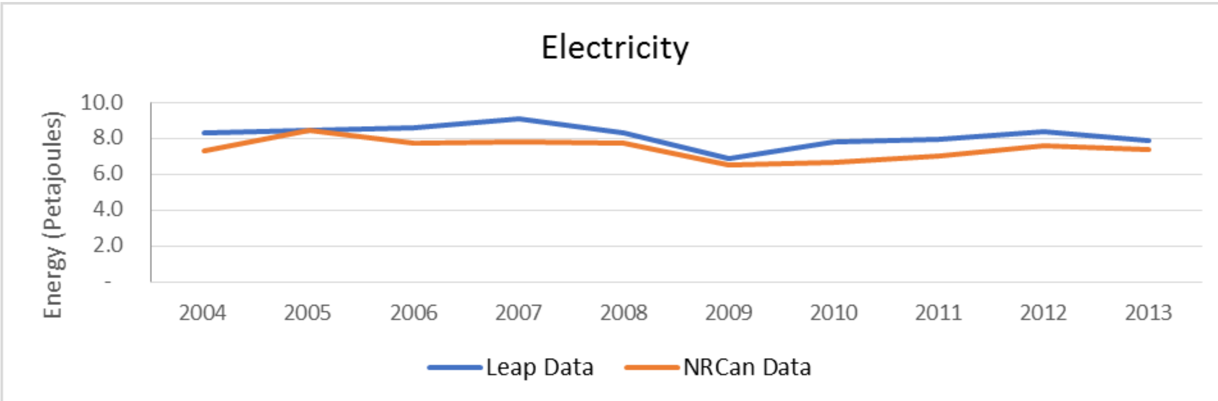


Figure B-1: Electricity Consumption of the Cement Industry in Canada

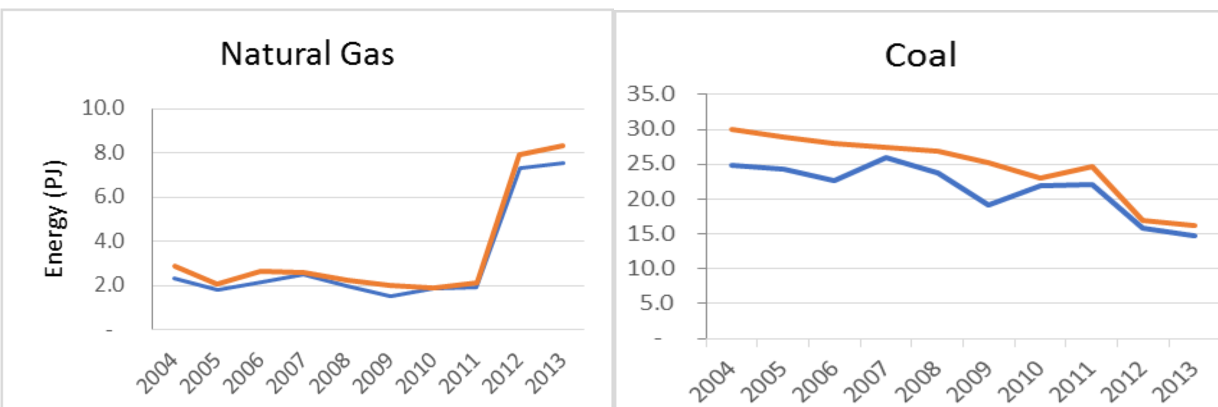


Figure B-2: Natural Gas and Coal verification

Appendix II-II: Energy efficiency measures in cement industry

Table B-1: Globally available energy efficiency measures for cement industry

Raw Material Preparation	
Efficient Transport System	The switch from pneumatic systems to mechanical conveyors energy savings is estimated at 2.0 kWh/tonne [243]. Conversion is cost effective only when replacement is needed to increase reliability and reduce downtime. Using pneumatic conveyors with high capacity bucket elevators can reduce power consumption by 2/3[424]. Upgrading the pneumatic system to a fluidized conveying system (FLC) can lead to an estimated 1 kWh/ton energy savings
Raw Meal Blending (Homogenizing) Systems	Improved raw material blending can reduce heat and power requirements for clinker production and increase production by 5% [277]. The use of gravity-type homogenizing silos can reduce energy consumption by 0.5 – 2.3 kWh/ton[425].
Advanced Raw Meal Grinding	Replacing ball mills with high efficiency roller mills, ball mills combined with high-pressure roller presses, or by horizontal roller mills can lead to energy savings of 6-7 kWh/ton [251, 277] An advantage of vertical roller mills is the combination of raw material drying with the grind process by using low-grade waste heat from the kilns or clinker coolers [255].
Separate Raw Material Grinding	Grinding materials with a high proportion in the raw mix in mills with low specific use and grinding materials that are harder to grind in vertical roller mills can be more efficient. Electricity savings are estimated at 0.55-0.77 kWh/ton [256]
Raw Meal Process Control	To avoid vibration trips of vertical roller mills a model-predictive multivariable controller can be used. Energy savings are estimated at 0.8-1 kWh/t [249].
High-Efficiency Classifiers/Separators	High-efficiency classifiers have 80-90% separation efficiency (compared to 50-60% of the first generation classifiers), an improved air distribution system, and advanced control of the air flow. Electricity savings of 2.5-3.4 kWh/t can be achieved [426].
Clinker Production	
Process Control & Management Systems – Kilns	Optimization of the combustion process and conditions using expert systems, model-predictive control (MPC), or fuzzy logic systems can lead to energy savings between 2.5 – 10 %, 0.04-0.17 MBTU/ton, respectively [256]. A process control of the clinker cooler can reduce energy consumption by 5%, increase cooler throughput by 10%, reduce free lime by 30%, and reduce NOx emissions by 20% [276].
Kiln Combustion System Improvements	Improved combustion systems optimize the mixing of combustion air and fuel while reducing the use of excess air and optimizing the shape of the flame. Fuel savings up to 10 can be achieved [278].
Mineralized Clinker	Mineralizers are used to improve raw mill burnability and can reduce the temperature in the sintering zone, which results in 5% fuel savings and 0.04-0.11 MBTU/ton clinker,. On the other hand, electricity consumption could increase by 0-0.09 kWh/t [256].

Indirect Firing	This technology is standard for modern plants. Because primary air supply is decoupled from the coal mill, lower percentages of primary air are used, which leads to energy savings of 43-63 kBTU/ton (by upgrading a mono- to multi-channel burner [256]. Upgrading a direct to an indirect firing system reduces energy by up to 162 kBTU/ton [277].
Seals Replacement	Seals are used to reduce false air penetration and heat losses at the kiln inlet and outlet. Upgrading seals can reduce fuel consumption, up to 0.01 MBTU/ton [427].
Refractories	Refractories protect the steel kiln shell against chemical, mechanical, and heat stress. New refractories have extended lifetimes and additional energy savings of about 54 kBTU/ton [277].
Efficient Kiln Drives	To rotate the kiln, synchronous motors are most often used. Upgrading the drives to single pinion drives with an air clutch and a synchronous motor would reduce power use by 0.5 kWh/ton [259].
Adjustable Speed Drive for Kiln Drives	Adjustable or variable speed drives for the kiln fan reduce maintenance costs and power consumption. Depending on the configuration of the plant , these drives can save up to 40% of electricity consumption [252]. Lafarge Canada´s Woodstock replaced their kiln fans with these drives and reduced electricity use by 5 kWh/t[253].
Conversion to Efficient Clinker Cooler Technology	Modern reciprocating grate coolers (3rd generation) increase the productivity of the kiln and have a higher heat recuperation efficiency (70-75%). By upgrading a planetary or rotary cooler, fuel savings up to 8% are possible. Upgrading modern coolers is economically attractive only when production needs to be expanded or a precalciner is installed [254, 256].
Optimization of Heat Recovery/Upgrade Clinker Cooler	The clinker cooler cools the clinker temperature from 1200 °C to 100 °C. Upgrading the clinker cooler can result in energy savings of 0.08 MBTU/ton [257].
Low Pressure Drop Cyclones for Suspension Preheaters	Upgrading cyclones will reduce the power consumption of the kiln exhaust gas fan system. For older kilns the energy consumption when replacing them can be reduced by 4kWh/ton [253].
Heat Recovery for Power Generation	The waste gas of the kiln, the clinker cooler system and the kiln pre-heater system can be used for power generation or raw/fuel drying. It can result in electricity savings of up to 30% and 10% primary energy saving [268].Only for long-dry kilns the temperature of the exhaust gas is high enough to operate cost effectively; for low heat recovery, ORC or Kalina cycles are possible but currently not economically attractive [428].
Dry Process Conversion to Multi-Stage Preheater Kiln	Installing a multi-stage suspension preheating system increase efficiency, reduce heat losses, and reduce energy consumption by up to 0.8 MBTU/ton [243]. When turning a long-dry kiln into a preheater kiln energy savings of about 1.4 MBTU/ton may result [277].
Increase the Number of Preheater Stages	Additional preheater stages will not always result in system energy savings. It depends on the moisture content of the fuel and raw materials. If heat is used for material or fuel drying, additional stages may not be energy effective. [429] Increasing a 5- to a 6-stage preheater may result in energy savings of 0.12 MBTU/ton clinker [277].
Installation or Upgrading of a Preheater to a Preheater/Precalciner Kiln	A preheater kiln can be converted to a multi-stage preheater precalciner kiln, which will increase the capacity while lowering the fuel consumption. Average energy savings are estimated to be 0.34 MBTU/ton [430].
Conversion of Long Dry Kiln to Preheater/Precalciner Kiln	Converting a long dry kiln can result in higher throughput, and energy savings are about 0.9 MBTU/ton clinker of thermal energy and 5 kWh/ton of electricity, respectively [256].

Increase the Number of Preheater Stages	Additional preheater stages will not always result in system energy savings. It depends on the moisture content of the fuel and raw materials. If heat is used for material or fuel drying, additional stages may not be energy effective [429]. Increasing a 5-to a 6-stage preheater may result in energy savings of 0.12 MBTU/ton clinker [277].
Installation or Upgrading of a Preheater to a Preheater/Precalciner Kiln	A preheater kiln can be converted to a multi-stage preheater precalciner kiln, which will increase the capacity while lowering the fuel consumption. Average energy savings are estimated to be 0.34 MBTU/ton [430].
Conversion of Long Dry Kiln to Preheater/Precalciner Kiln	Conversion of a long dry kiln can result in higher throughput and energy savings are about 0.9 MBTU/ton clinker of thermal energy, 5 kWh/ton of electricity [256].

Appendix III: Supplementary information for Chapter 4

Appendix III-I: Iron and steel production processes

The main energy consuming sub-processes in the iron and steel industry are:

Sinter plant

In a sinter plant, the raw materials are physically and metallurgically prepared to be fed into the blast furnace. This ultimately helps improve the performance of the blast furnace. The feedstock for the sinter plant are a combination of iron ore, coke breeze and iron bearing martials [317, 431].

Coke oven plant

Certain types of coal such as coking or bituminous could be converted to coke in the pyrolysis process, during which coal is heated in an oxygen-free environment [32] [317]. In general, one tonne of dry coal is consumed to produce 700-800 kg dry coke and 140-200 kg coke oven gas (COG) [317].

Blast furnace

In a blast furnace (BF), pig iron is produced from iron ore. The main inputs to the blast furnace are iron feedstock such as iron ore and sinter, reducing agents such as coke, and additives such as slag formers. Iron oxides are reduced to iron metals by CO, which is the product of the reaction between air blast and reducing agents. [317]. As the major energy-consumer sub-sector in the iron and steel industry, the blast furnace accounts for more than 50% of the energy consumption in iron and steel enterprises [319].

[32] Other materials containing carbon such as petroleum coke and crushed rubber tire could also be used in small quantities.

Basic oxygen furnace (BOF)

In the basic oxygen furnace, the carbon content of the hot metal feedstock is reduced, the content of the desirable foreign elements is adjusted, and the undesirable elements are removed to the extent possible. All of this occurs mainly through oxidization. The output of the blast furnace is treated before being used as the feed for the BOF where it is oxidized. The BOF products then undergo secondary treatment and casting [317, 318].

Electric arc furnace (EAF)

Direct smelting of ferrous scrap is performed in the EAF. In order to adjust the desired concentration of non-ferrous metals in the finished steel, some ferroalloys might also be added to the feedstock. In the EAF, the feedstocks (mainly steel scrap) are melted and the steel products will be fed into the ladle furnace treatment for quality adjustment. The semi-finished product is then cast to produce the final product [317].

Casting, rolling, and finishing

The products of both BOF and EAF furnaces are cast in a continuous casting process (in Canada, 97% of the products of the steelmaking process undergo continuous casting) to produce semi-finished shapes such as slabs, blooms, etc. [111]. The casting process is usually followed by rolling, where final products such as coiled strips and steel sheets are produced. Processes such as hot forming, cold rolling, tempering, and pickling are known as finishing processes and are used in only some of the steel processing [307].

Appendix III-II: Long-term steel production in Canada

To predict future steel production in Canada, it is considered that the economic growth and steel use intensity are interrelated such that the rate of steel consumption versus GDP growth follows an inverse U-shape curve [432]. More precisely, as the economy grows and becomes more mechanized and construction expands, the rate of steel consumption increases accordingly. Consumption reaches a peak and thereafter declines and stabilizes as society moves towards a service-based economy [286, 432]. The Canadian per capita steel demand projection till 2050 is shown in Table 10 [433].

Table C-1: Crude steel demand per capita 2006-2050 [433]

		Low-demand Scenario			High-demand Scenario		
Year	2006	2015	2030	2050	2015	2030	2050
Kg/Cap	590	550	525	500	550	525	500

As shown in Table 10, the projected per-capita steel demand is similar in both low and high-demand scenarios. This is in line with IIASA's general forecast of steel demand in the industrialized world, which projects that steel demand is stabilized at 500 kg/capita [434]. In addition, assuming that the iron and steel industry in Canada and US share considerable similarities [435], and knowing that the per capita steel demand stabilizes at a per capita GDP of more than $30,000 (at around 500kg/capita) [286], it is reasonable that the data presented in Table 10 are justified to be used in this study. An analysis of the historical data (2003-2010) shows that in the past decade the per capita steel demand was around 583 kg/capita (comparable to the data reported by the IEA [433]) except for the post-economic crisis in 2009 when the figure dropped to 407 kg/capita (Figure 12) [199, 314].

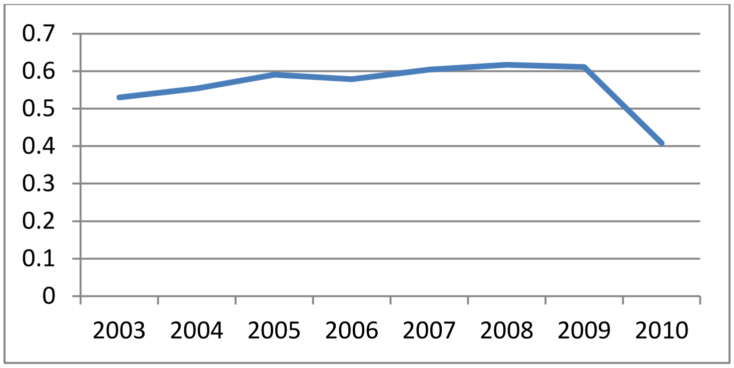


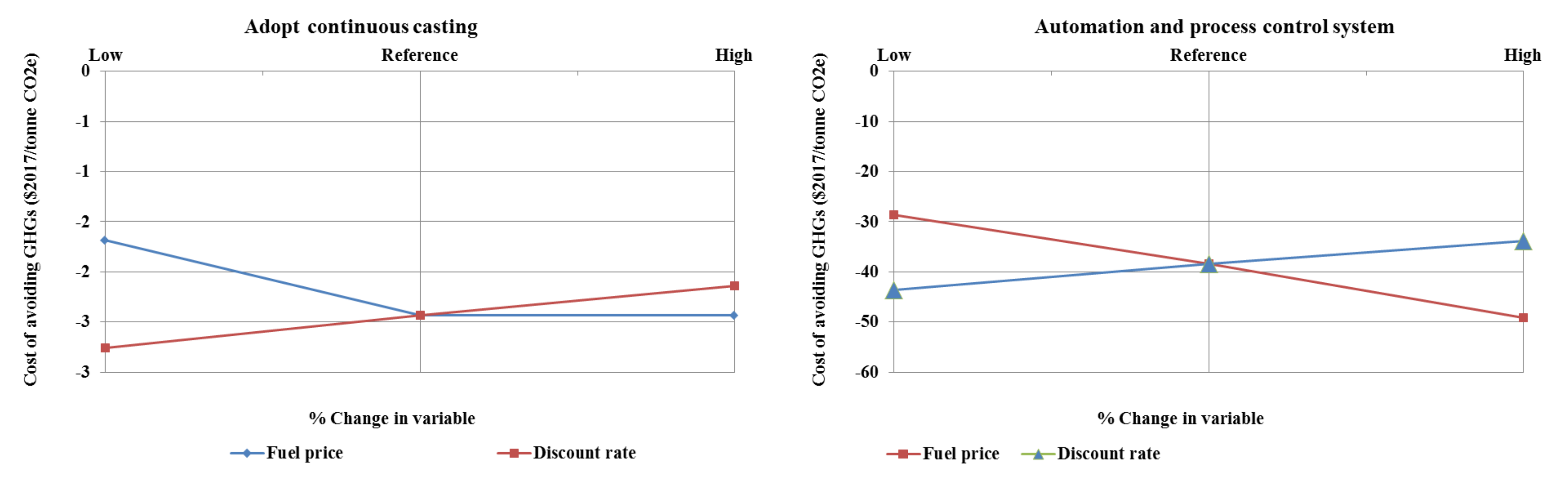
Figure C-1: Per capita steel consumption in Canada (tonnes) [199, 314]

Historically, around 10% of the demand is met by import and the rest is domestically produced [314]. Of the nationally produced steel, around 90% is produced in two of the eastern provinces, Ontario (68%) and Quebec (22%). For simplicity, these shares are considered to be unchanged throughout the time period of the study.

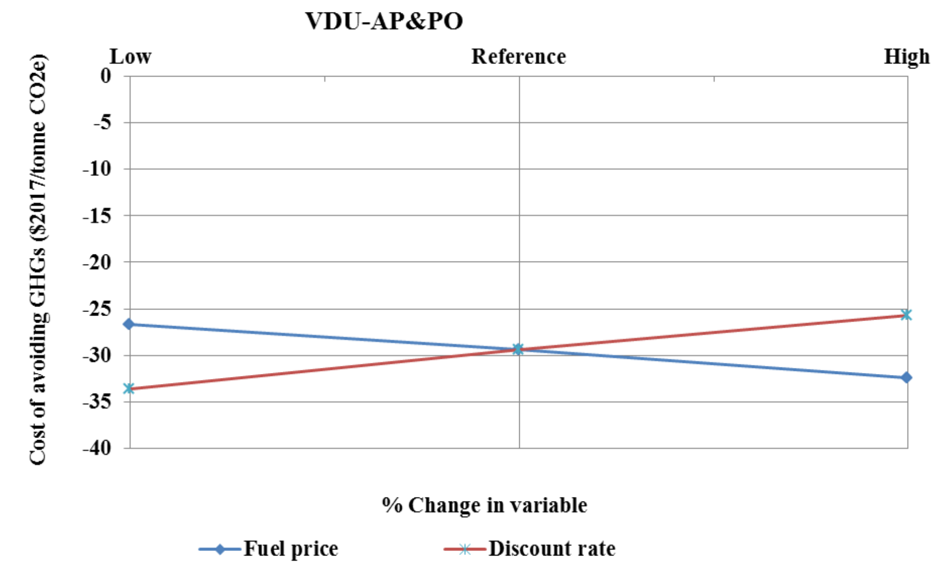
The medium-growth scenario (M1) developed by Statistics Canada's Demography Division [436] was used to forecast the future population of the country. According to predictions, the country's population will reach 43.8 and 48.5 million people in 2036 and 2050, respectively. Using this and the data reported in Table 10, the total steel in Canada was predicted. Although the biggest consumers of steel are expected to be in the west (mainly Alberta and Saskatchewan) due to fast-growing energy industries there, Ontario is expected to play the major role in steel production mainly because of the proximity to the iron mines. Moreover, currently all four Canadian integrated steel plants are in Ontario [111].

Appendix III-III: Sensitivity analysis

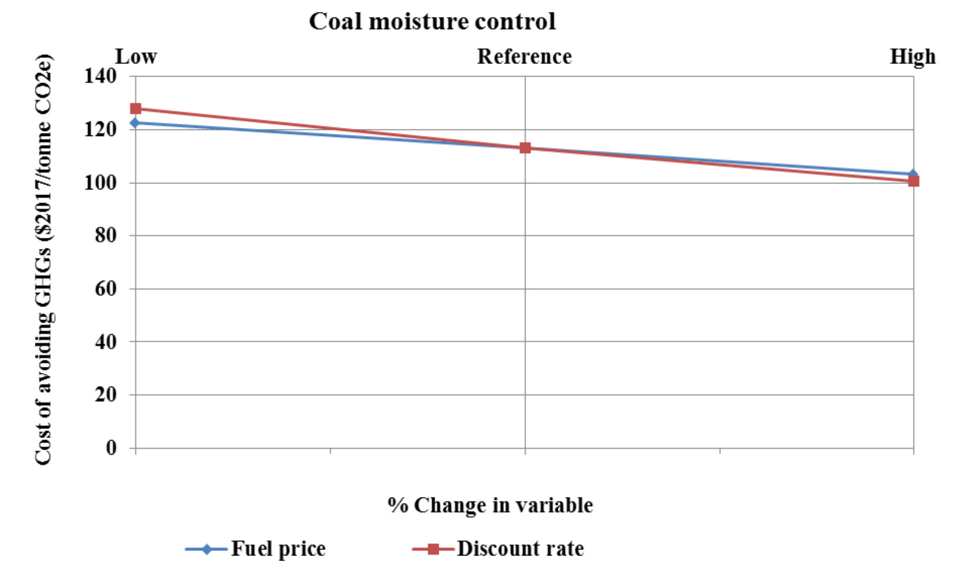
Figure C-2: Sensitivity of the results to input parameters



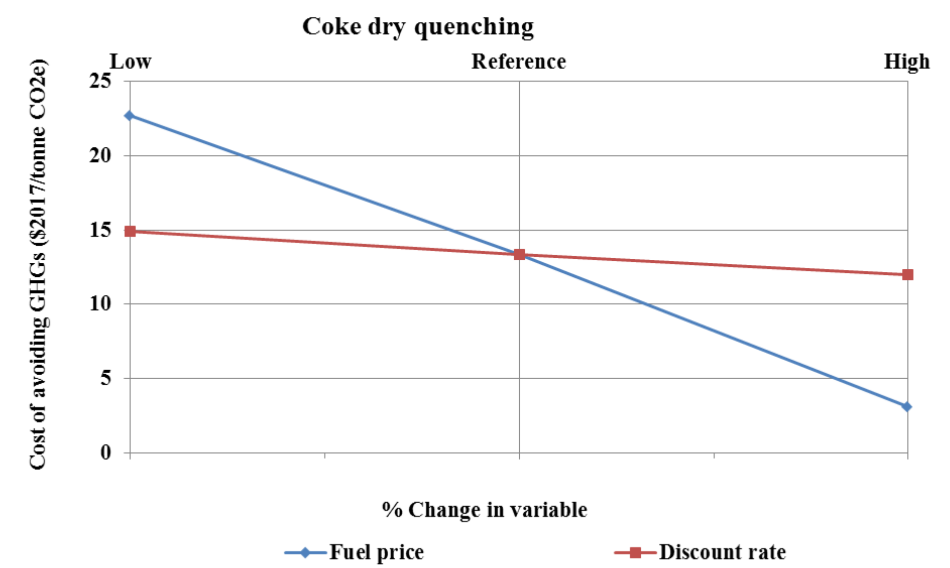
(a)	(b)


VDU-AP&PO
Low
Reference
High
0
-5
-10
-15
-20
-25
-30
-35
-40
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

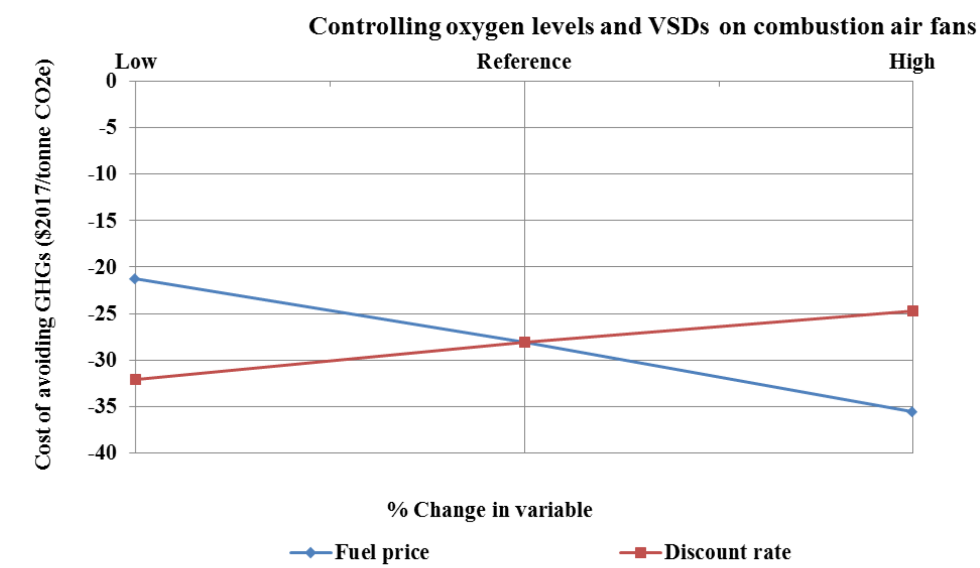
(c)


Coal moisture control
Low
Reference
High
140
120
100
80
60
40
20
0
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

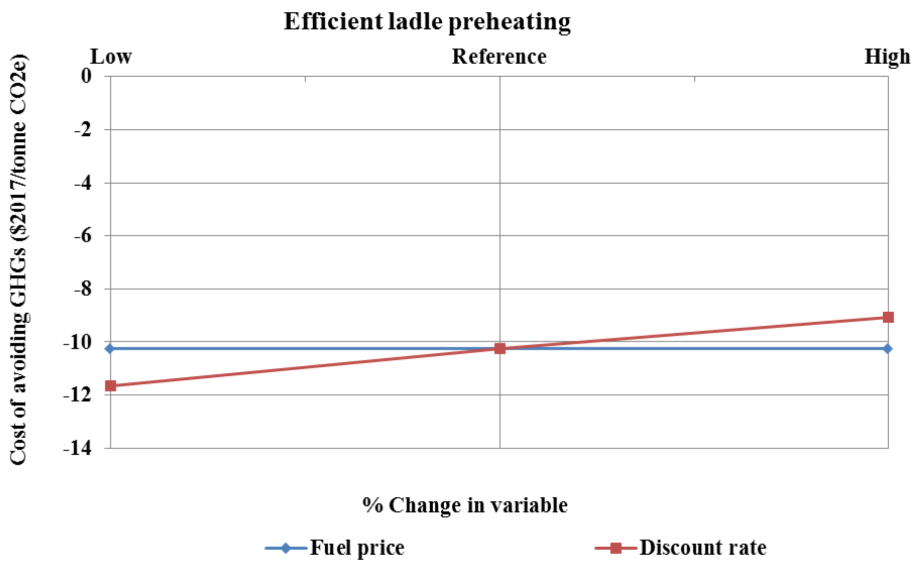
(d)


Coke dry quenching
Low
Reference
High
25
20
15
10
5
0
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

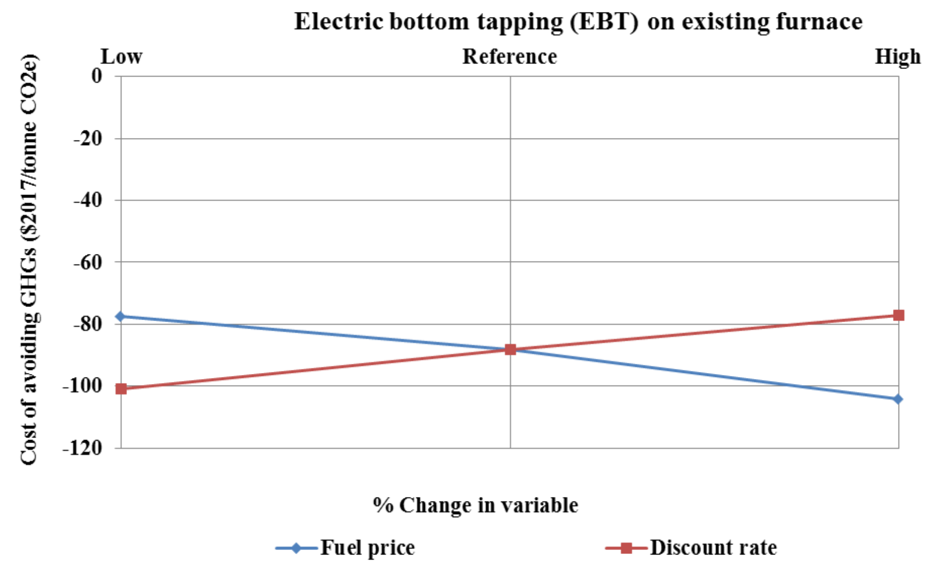
(e)


Controlling oxygen levels and VSDs on combustion air fans
Low
Reference
High
0
-5
-10
-15
-20
-25
-30
-35
-40
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

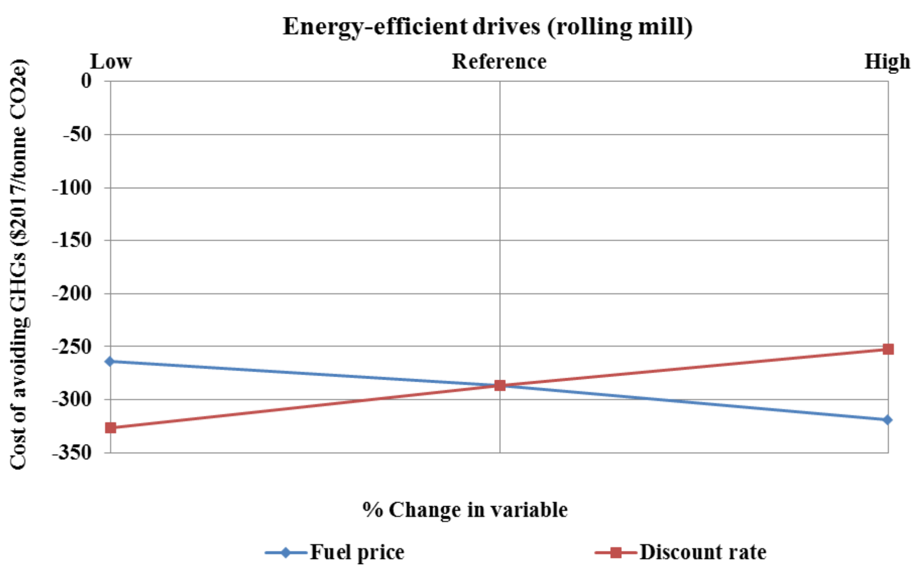
(f)


Efficient ladle preheating
Low
Reference
High
0
-2
-4
-6
-8
-10
-12
-14
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

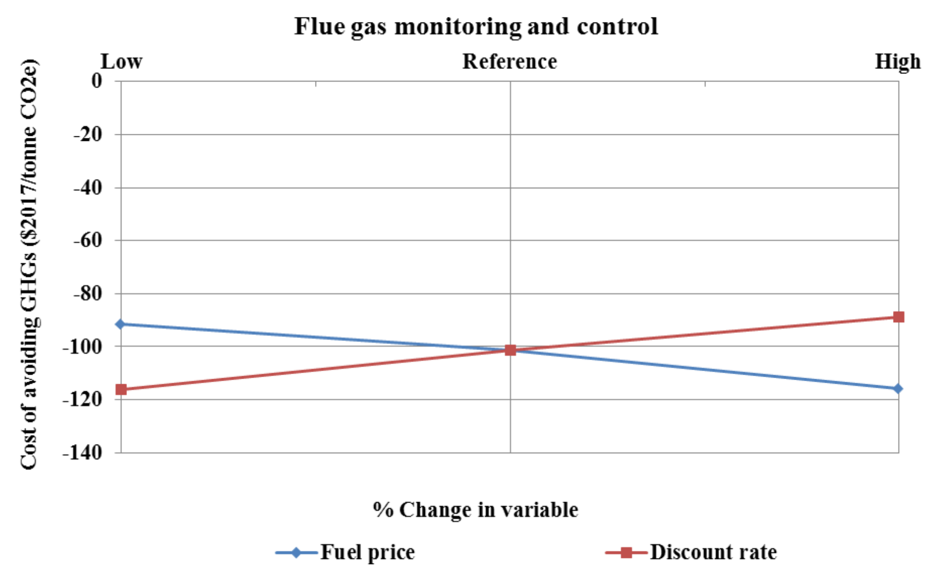
(g)


Electric bottom tapping (EBT) on existing furnace
Low
Reference
High
0
-20
-40
-60
-80
-100
-120
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

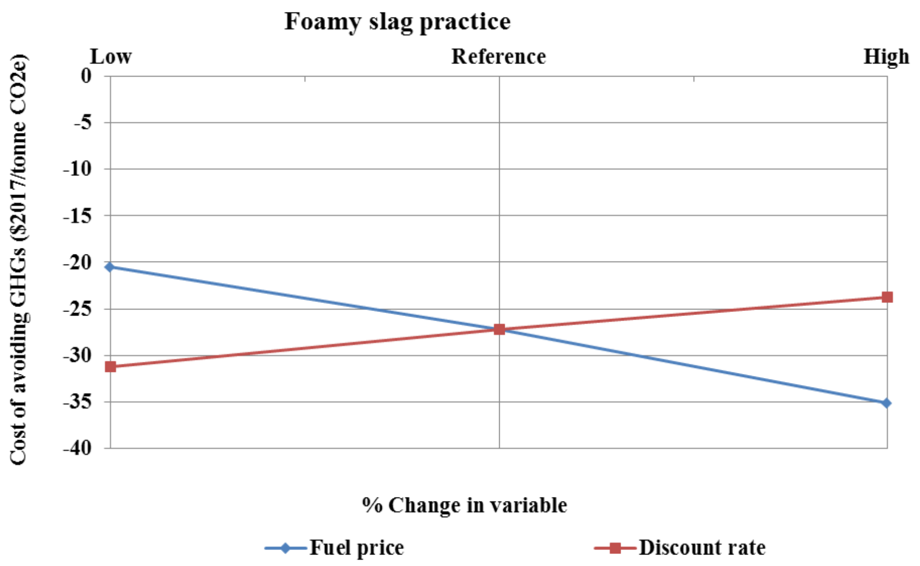
(h)


Energy-efficient drives (rolling mill)
Low
Reference
High
0
-50
-100
-150
-200
-250
-300
-350
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

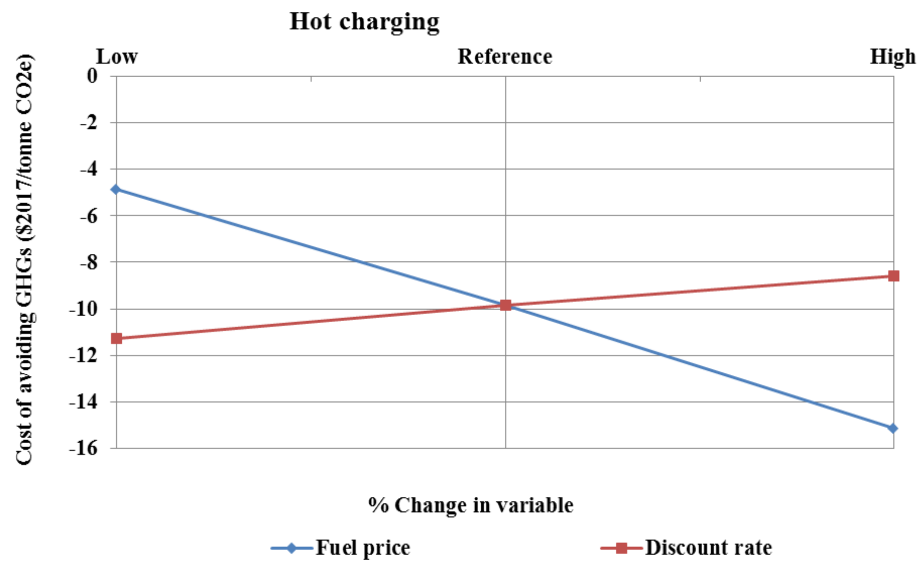
(i)


Flue gas monitoring and control
Low
Reference
High
0
-20
-40
-60
-80
-100
-120
-140
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

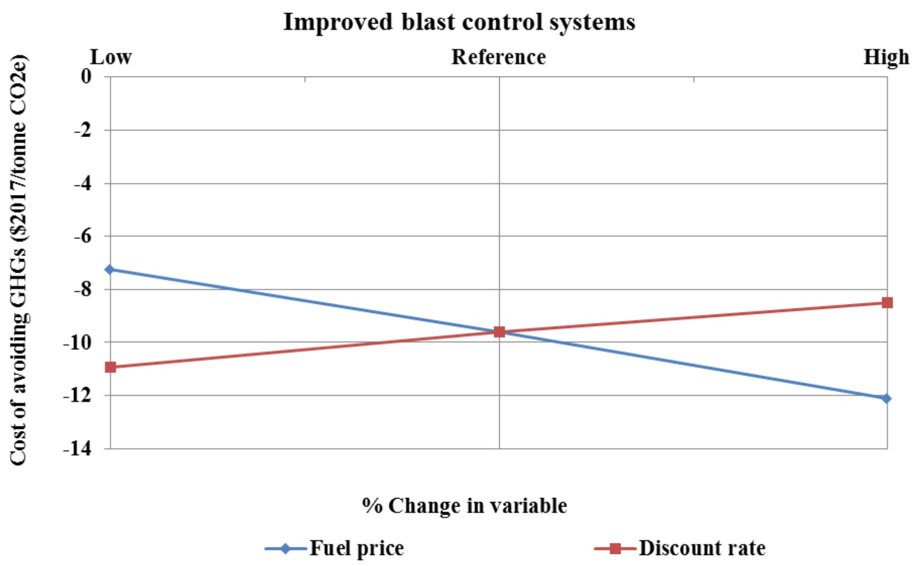
(j)


Foamy slag practice
Low
Reference
High
Cost of avoiding GHGs ($2017/tonne CO2e)
0
-5
-10
-15
-20
-25
-30
-35
-40
% Change in variable
Fuel price
Discount rate

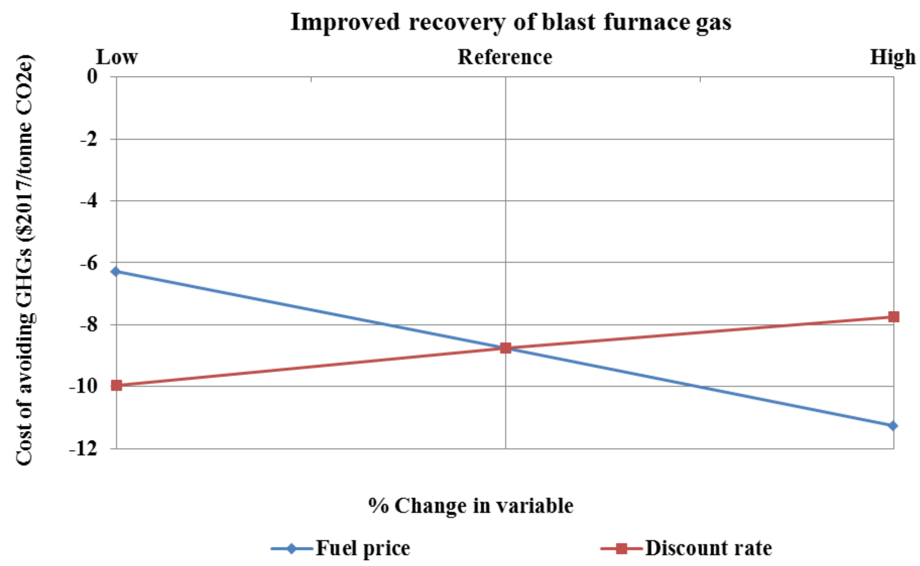
(k)


Hot charging
Low
Reference
High
Cost of avoiding GHGs ($2017/tonne CO2e)
0
-2
-4
-6
-8
-10
-12
-14
-16
% Change in variable
Fuel price
Discount rate

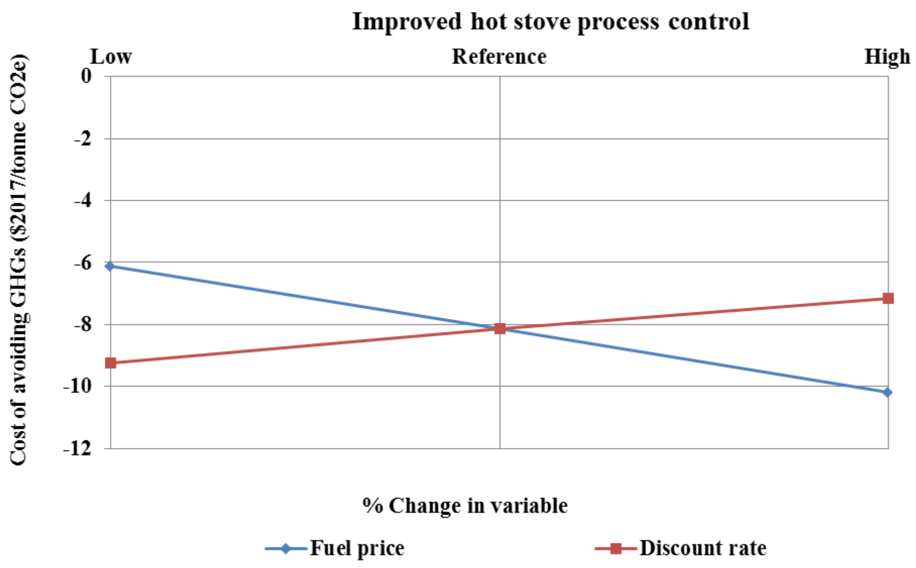
(l)


Improved blast control systems
Low
Reference
High
Cost of avoiding GHGs ($2017/tonne CO2e)
0
-2
-4
-6
-8
-10
-12
-14
% Change in variable
Fuel price
Discount rate

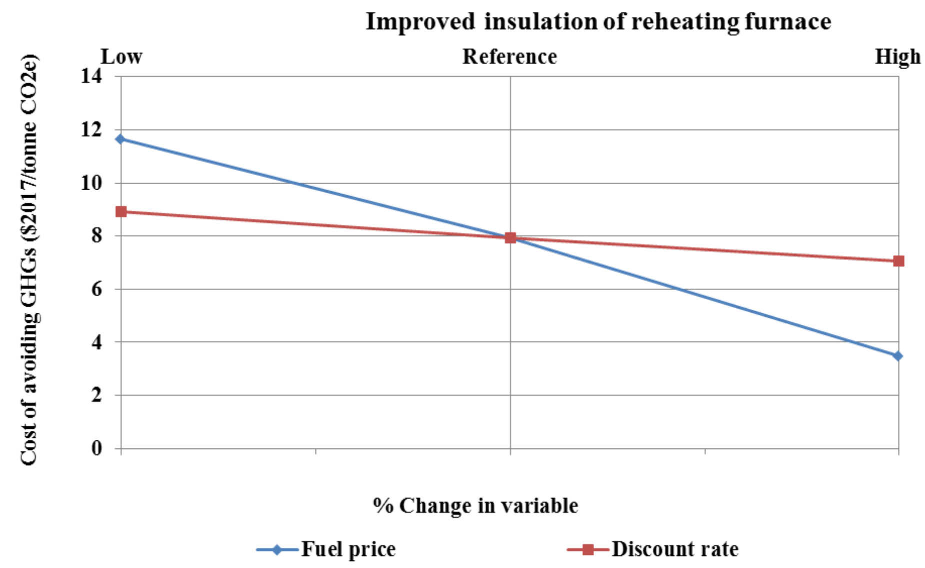
(m)


Improved recovery of blast furnace gas
Low
Reference
High
Cost of avoiding GHGs ($2017/tonne CO2e)
0
-2
-4
-6
-8
-10
-12
% Change in variable
Fuel price
Discount rate

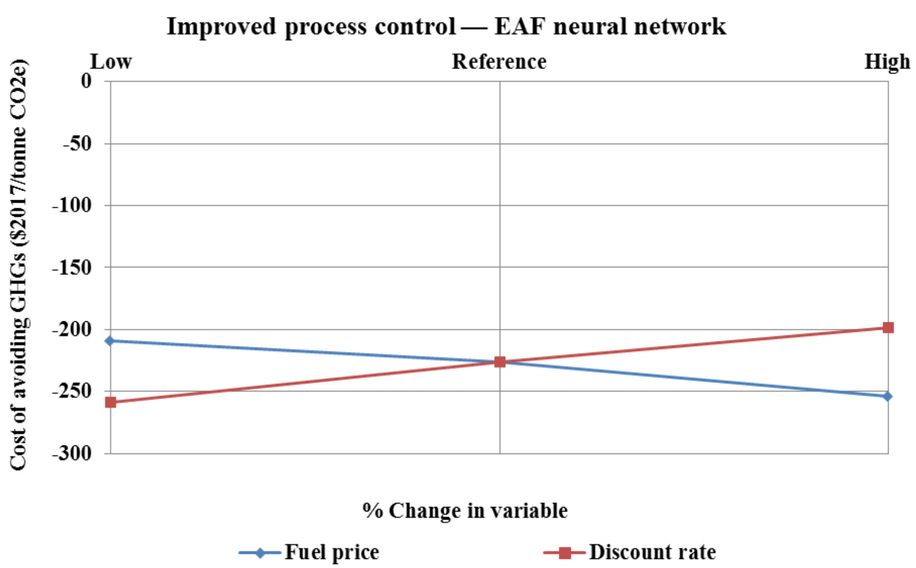
(n)


Improved hot stove process control
Low
Reference
High
0
-2
-4
-6
-8
-10
-12
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

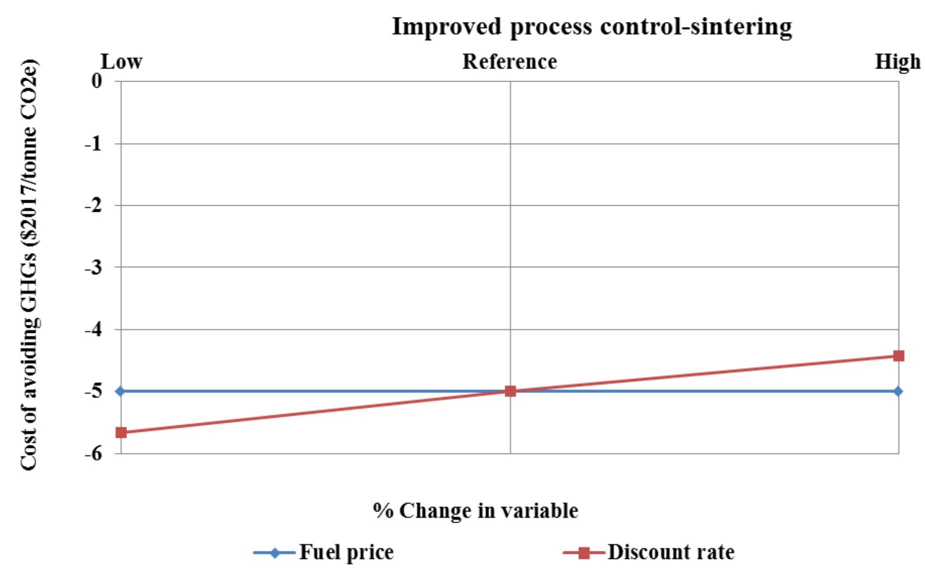
(o)


Improved insulation of reheating furnace
Low
Reference
High
14
12
10
8
6
4
2
0
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

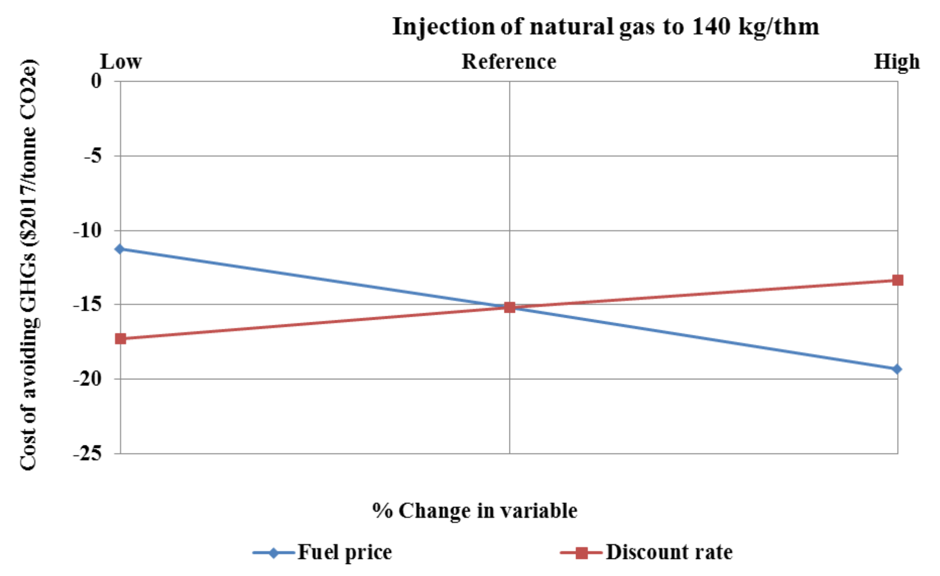
(p)


Improved process control — EAF neural network
Low
Reference
High
0
-50
-100
-150
-200
-250
-300
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

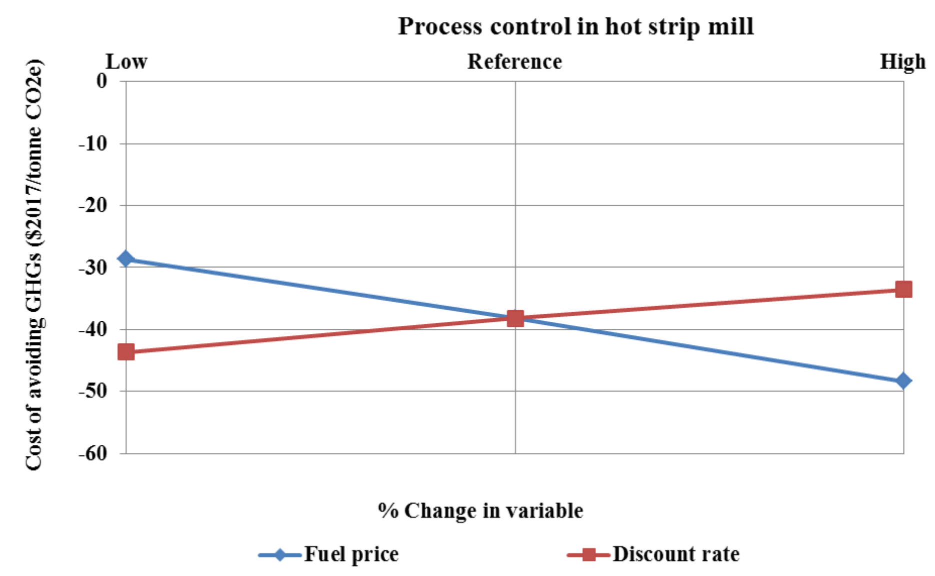
(q)


Improved process control-sintering
Low
Reference
High
0
-1
-2
-3
-4
-5
-6
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

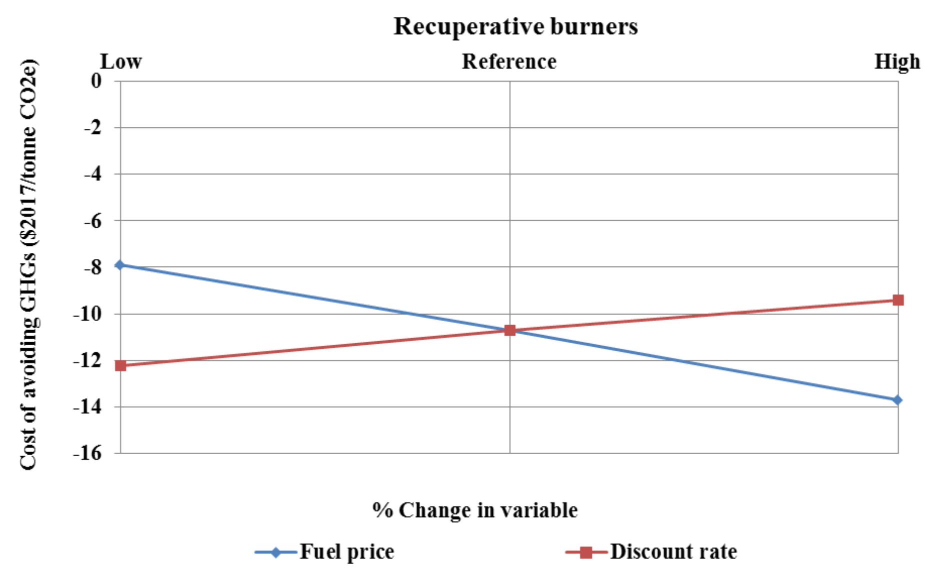
(r)


Injection of natural gas to 140 kg/thm
Low
Reference
High
0
-5
-10
-15
-20
-25
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

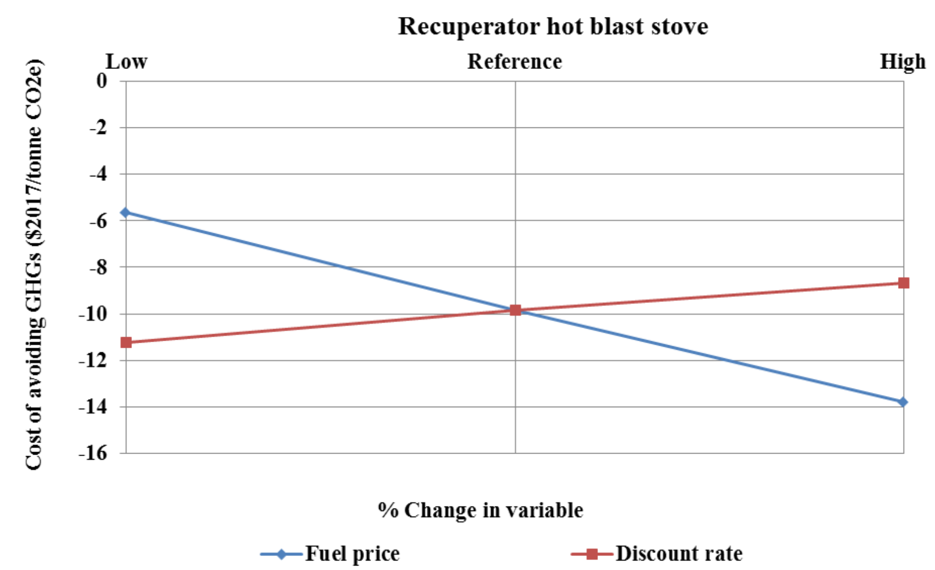
(s)


Process control in hot strip mill
Low
Reference
High
0
-10
-20
-30
-40
-50
-60
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

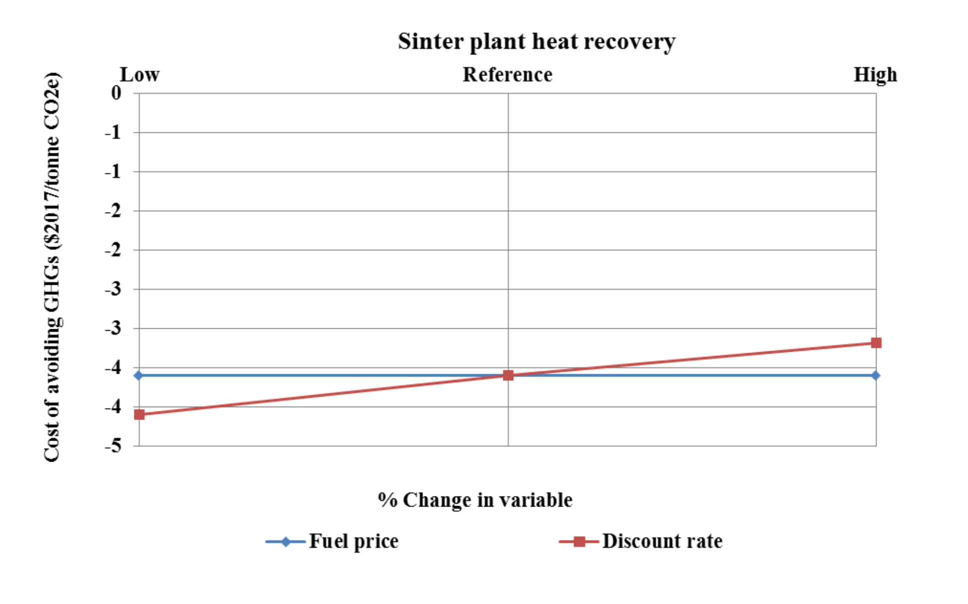
(t)


Recuperative burners
Low
Reference
High
0
-2
-4
-6
-8
-10
-12
-14
-16
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

(u)

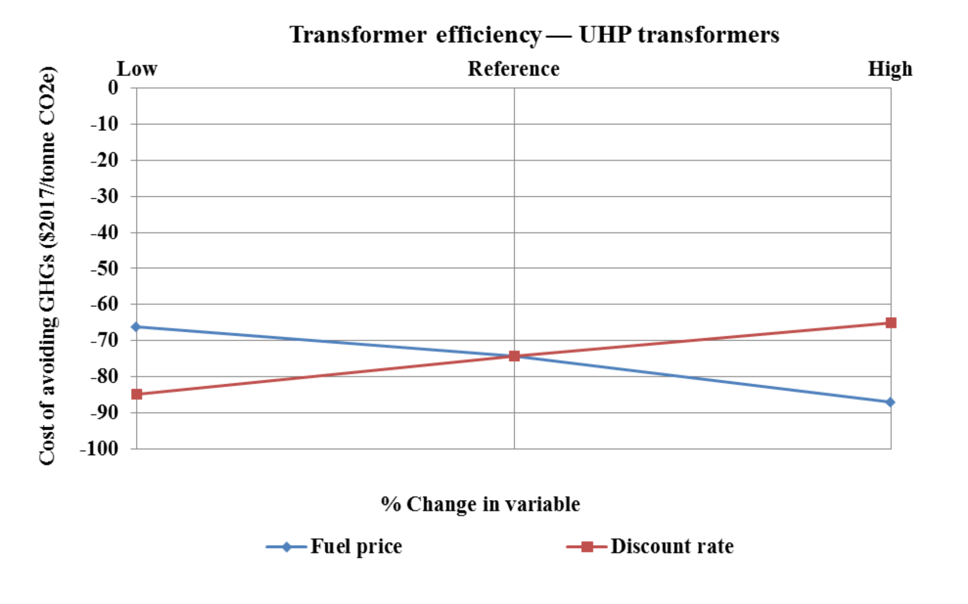

Recuperator hot blast stove
Low
Reference
High
0
-2
-4
-6
-8
-10
-12
-14
-16
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

(v)



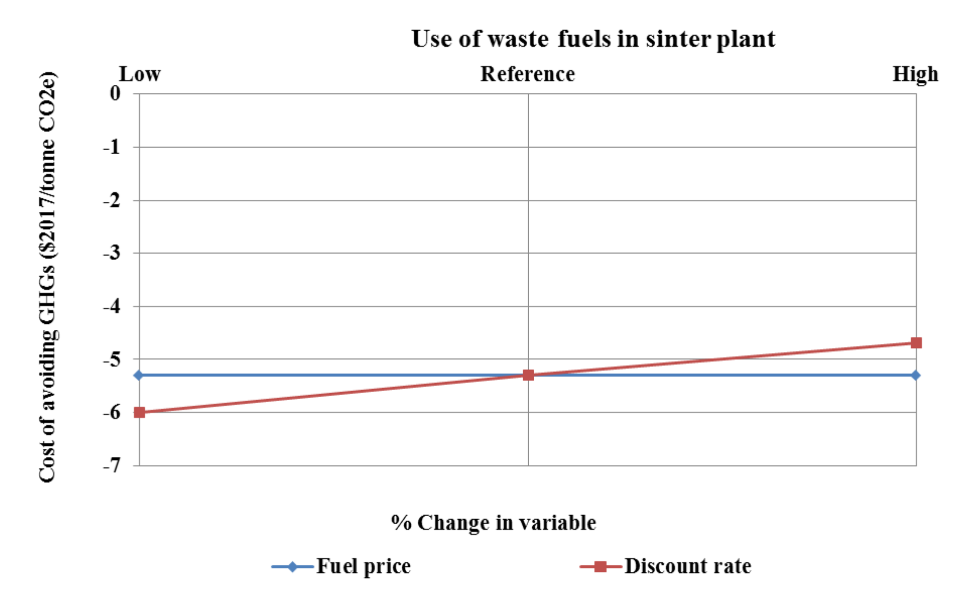
Sinter plant heat recovery
Low
Reference
High
0
-1
-1
-2
-2
-3
-3
-4
-4
-5
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

(w)



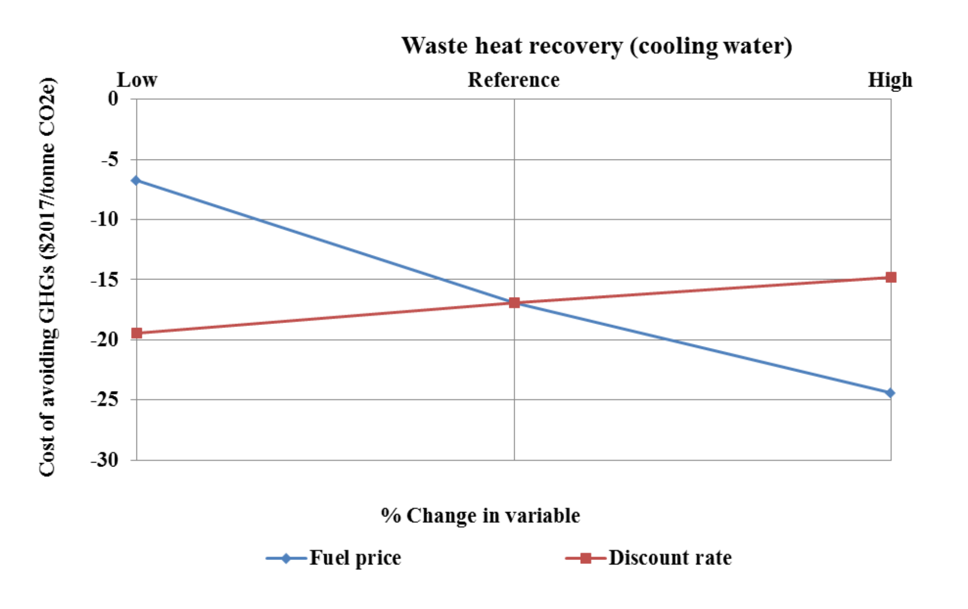
Transformer efficiency — UHP transformers
Low
Reference
High
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

(x)



Use of waste fuels in sinter plant
Low
Reference
High
0
-1
-2
-3
-4
-5
-6
-7
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

(y)



Waste heat recovery (cooling water)
Low
Reference
High
0
-5
-10
-15
-20
-25
-30
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate

(z)

Appendix IV: Supplementary information for Chapter 5

Appendix VI-I: Process Modelling in Aspen HYSYS

Atmospheric and vacuum distillation units

Figure A-1 shows the Aspen HYSYS process flow diagram of the atmospheric distillation unit and vacuum distillation unit with their corresponding heat exchangers, columns, coolers, pump-around units, and furnaces. The crude distillation unit has the capacity to process 150,000 barrels (23800 cubic meters) of synthetic crude oil (SCO) per day. Table A-1 lists the properties of synthetic crude oil. The corresponding temperatures and heat duty of the feed and product streams are presented in Table A-2. The improvements considered in these units are mainly preheating crude feed to the furnace and the furnace combustion air. The configuration of the system remains the same; however, the heat exchanger sizes were increased to achieve targeted heat duty. The base case temperature of the atmospheric feed to the furnace is 254^{o}C.

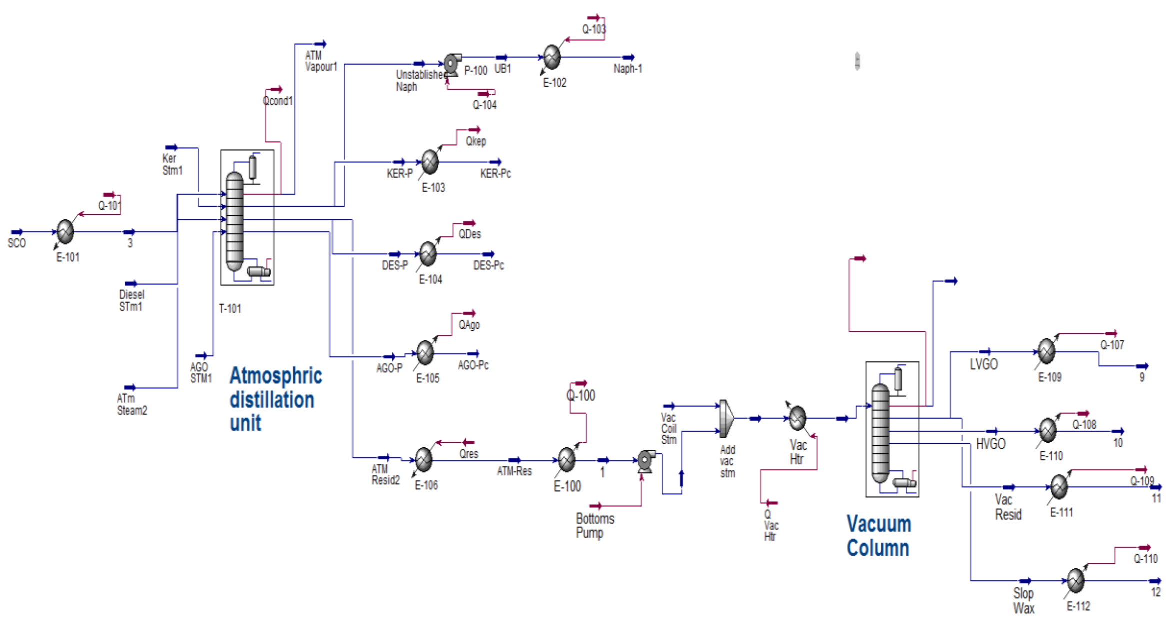


Figure D-1: Aspen HYSYS process flow diagram of the atmospheric and vacuum distillation units

Table D-1: Properties of synthetic crude oil

Properties	Unit
Std. liquid density (kg/m3)	866.2
Sulfur by wt (%)	0.15
Nitrogen by wt (%)	0.06
Rams carbon residue by wt (%)	0.12
Kinematic viscosity (cSt) @ 40 (C)	3.8
Paraffins by vol (%)	17.2
Naphthenes by vol (%)	32.4
Arom by vol (%)	50.4
Aniline point (C)	48.4

Table D-2: Feed and products stream temperature of the CDU

Stream	Supply Temperature (^oC)	Target Temperature (^oC)	Heat Duty (kW)
Crude to desalter	50	128	38266
Crude to furnace	128	365	169216
Ker-P	227	50	14597
Des-P	275	50	20082
AGO	294	50	11744
LVGO	206	50	22161
HVGO	307	50	11572
Vac-Res	308	50	3428
PA1	245	75	10800
PA2	290	121	18627
PA3	325	180	13504
VPA1	206	95	30243
VPA2	307	224	19566
Naph feed	55	122	7522
Naphtha	178	113	63925

8.1.1.1. Catalytic reforming unit

Figure A-2 shows the Aspen HYSYS process flow diagram of the catalytic reforming unit with its corresponding heat exchangers, distillation columns, coolers, compressors, reactors, and furnaces. The unit has the capacity to process 25,000 barrels of feed per day. The feed stream temperature to each of the reactors is maintained at 523^oC. The temperature and flow rates of the feed and product streams are presented in Table A-3. The improvement considered in this unit is mainly preheating feeds into the furnace. The system configuration remains the same; however, the heat exchanger sizes were increased to achieve the targeted heat duty.

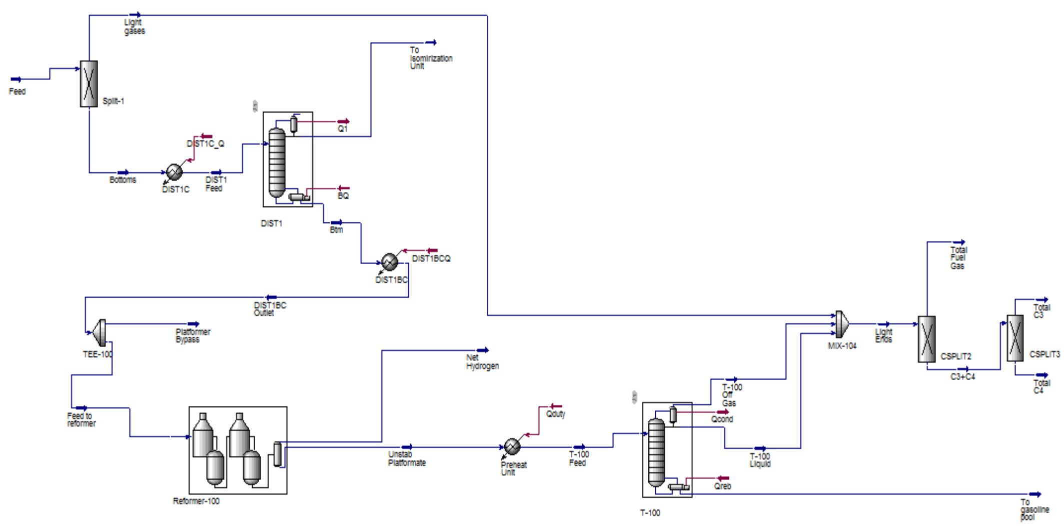


Figure D-2: Aspen HYSYS process flow diagram of the catalytic reforming unit

Table D-3: Temperature and flow rate of the feed and products of the catalytic reforming unit

Streams	Temperature (^oC)	Flow rate (kg/h)
Feed to unit	30	120000
Feed to reformer	150	76549
Net hydrogen	28	6274
Light product	211.7	28963
Reformate	314.6	41403

8.1.1.2. Delayed coking unit

Figure A-3 shows the Aspen HYSYS process flow diagram of the delay coker unit with its corresponding, distillation columns, coolers, pump-around units, and coker (furnace). The unit has the capacity to process 153,000 barrels (24300 cubic meters) of vacuum residue per day. The corresponding temperature and flow rates of the feed and product streams are presented in Table A-4. The improvement considered in this unit is mainly preheating the furnace combustion air. The system configuration remains the same; however, the heat exchanger was added to achieve targeted heat duty.

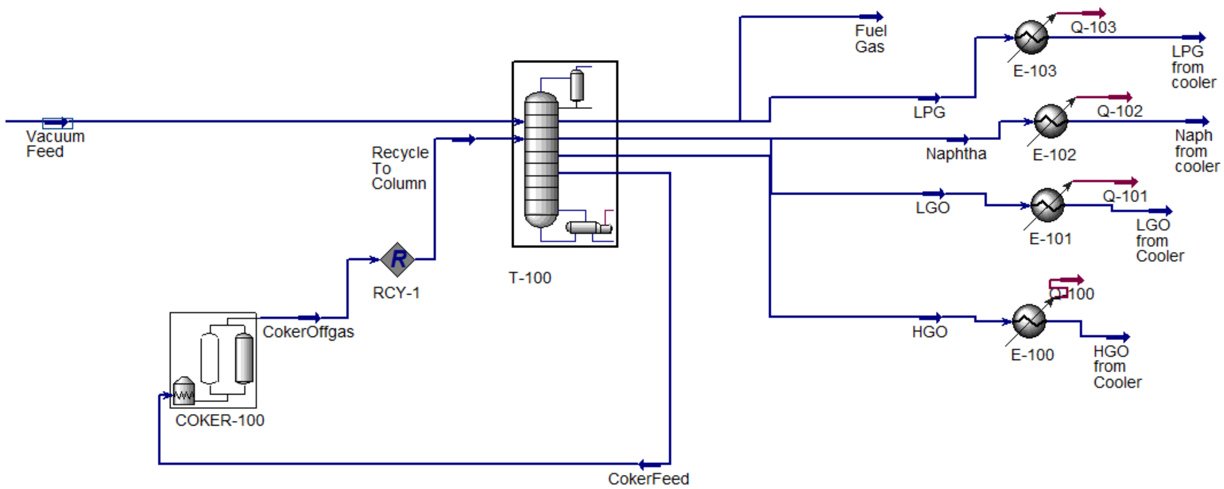


Figure D-3: Aspen HYSYS process flow diagram of the delayed coker unit

Table D-4: Temperature and flow rates of feed and product stream of the delay coker unit

Stream	Flow rate (m^3/day)	Temperature (^{o} C)
Vacuum Feed	24324.32	316
LPG	0.00	65
Naphtha	2947.06	125
LGO	8364.71	173
HGO	933.07	338

8.1.1.3. Fluid catalytic cracking, hydrocracking and the naphtha hydrotreating units

Figures A-4 and A-5 show the Aspen HYSYS process flow diagram of the fluid catalytic cracking (FCC) and naphtha hydrotreating units. The hydrocracking unit considered in this study is similar to that of hydrotreating unit. These units require calibration to predict product yields. In this study, because no data was available, each unit was calibrated using Aspen HYSYS' default calibration factors. A processing capacity of 22,436 m^3/day of heavy gas oil from a delayed coker was considered for the FCC unit. A processing capacity of 15,898 m^3/day of light and heavy gas oils from a delayed coker was considered as feed for the hydrocracker unit, while 3,453 m^3/day of naphtha was considered for the naphtha hydrotreating unit. The improvements considered in these units are either feed preheating or the combustion air. The configuration of the systems remains the same; however, the heat exchanger sizes were increased to achieve targeted heat duty.

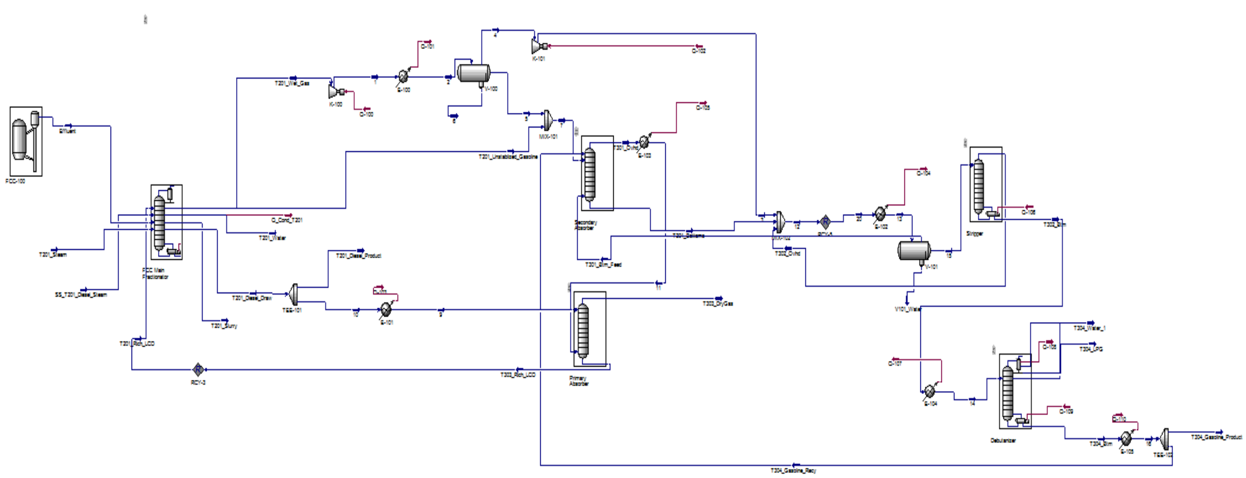


Figure D-4: Aspen HYSYS process flow diagram of the fluid catalytic cracking unit

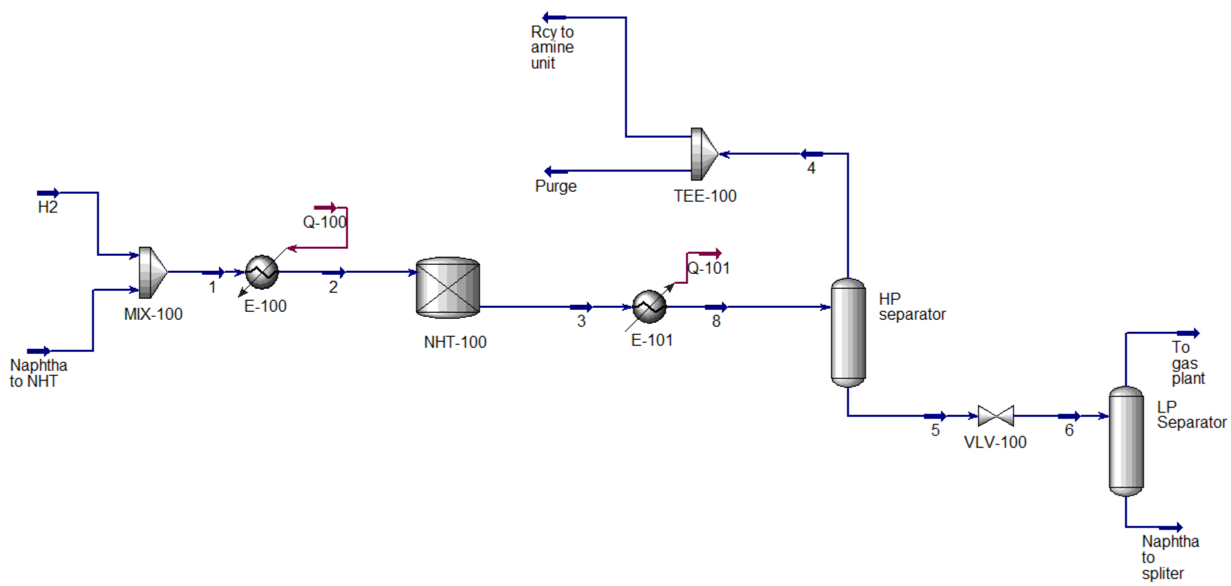


Figure D-5: Aspen HYSYS process flow diagram of the naphtha hydrotreating unit

8.1.1.4. Isomerization unit

The isomerization unit and its proposed modification, using heat pump models, is simulated in the Aspen HYSYS 8.8 simulation program. A mixture of 527.3 kmol/h propane (0.1%), i-butane (0.44%), n-butane (0.54%), and n-pentane (0.02%) was considered as the feed stream. The feed conditions (i.e., temperature, pressure, feed composition, and flow rate) into the column were maintained in all cases considered. The temperatures of the feed stream and the top and bottom product are 55°C, 40 °C, and 59.3°C, respectively. The corresponding pressures of the feed stream and top and bottom product are 689.5, 690, and 709 kPa, respectively. The Peng-Robinson property package was used to develop the system models. This equation-of-state model is adequate to predict the equilibrium of light hydrocarbon mixtures. The Aspen HYSYS simulation model is for the base case model; the modified model is presented in Figure A-6 (a) and (b), respectively.

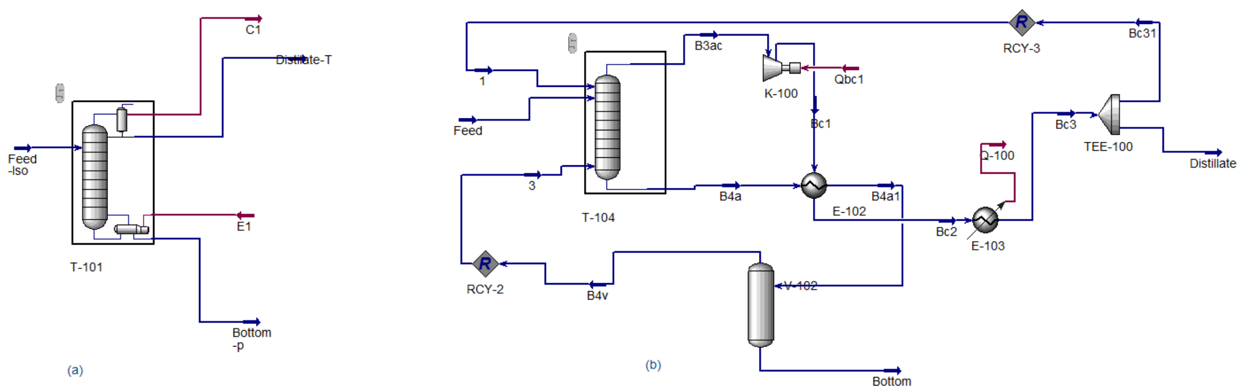


Figure D-6: Aspen HYSYS process flow diagram of (a) base case isomerization unit and (b) modified isomerization unit

8.1.1.5. Alkylation unit

The alkylation unit and its proposed modification, using heat pump models, is simulated in the Aspen HYSYS 8.8 simulation program. A feed stream flow rate of 187.5 kmol/h was considered. Table A-6 presents the feed composition. The feed operating conditions (i.e., temperature, pressure, feed composition, and flow rate) into the column were maintained in all cases. The temperatures of the feed stream and the top and bottom product are 69.5^{o}C, 45^{o}C, and 64^{o}C, respectively. The corresponding pressures of the feed stream and the top and bottom product are 975.1, 559.8, and 668.8 kPa, respectively. The Peng-Robinson property package was used to develop the system models. This equation-of-state model is adequate to predict the equilibrium of light hydrocarbon mixtures. The Aspen HYSYS simulation model is for the base case model; the modified model is presented in Figure A-7 (a) and (b).

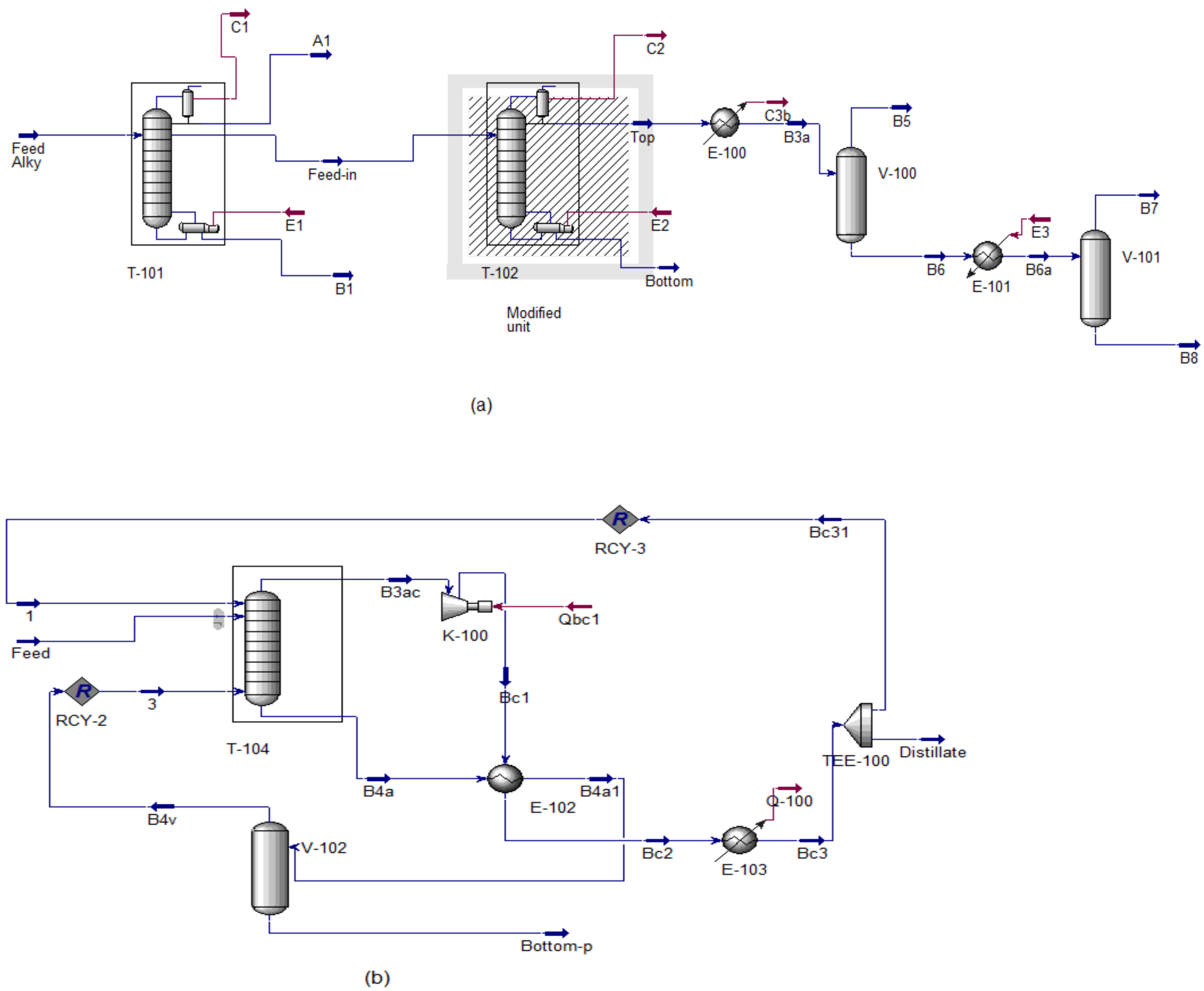


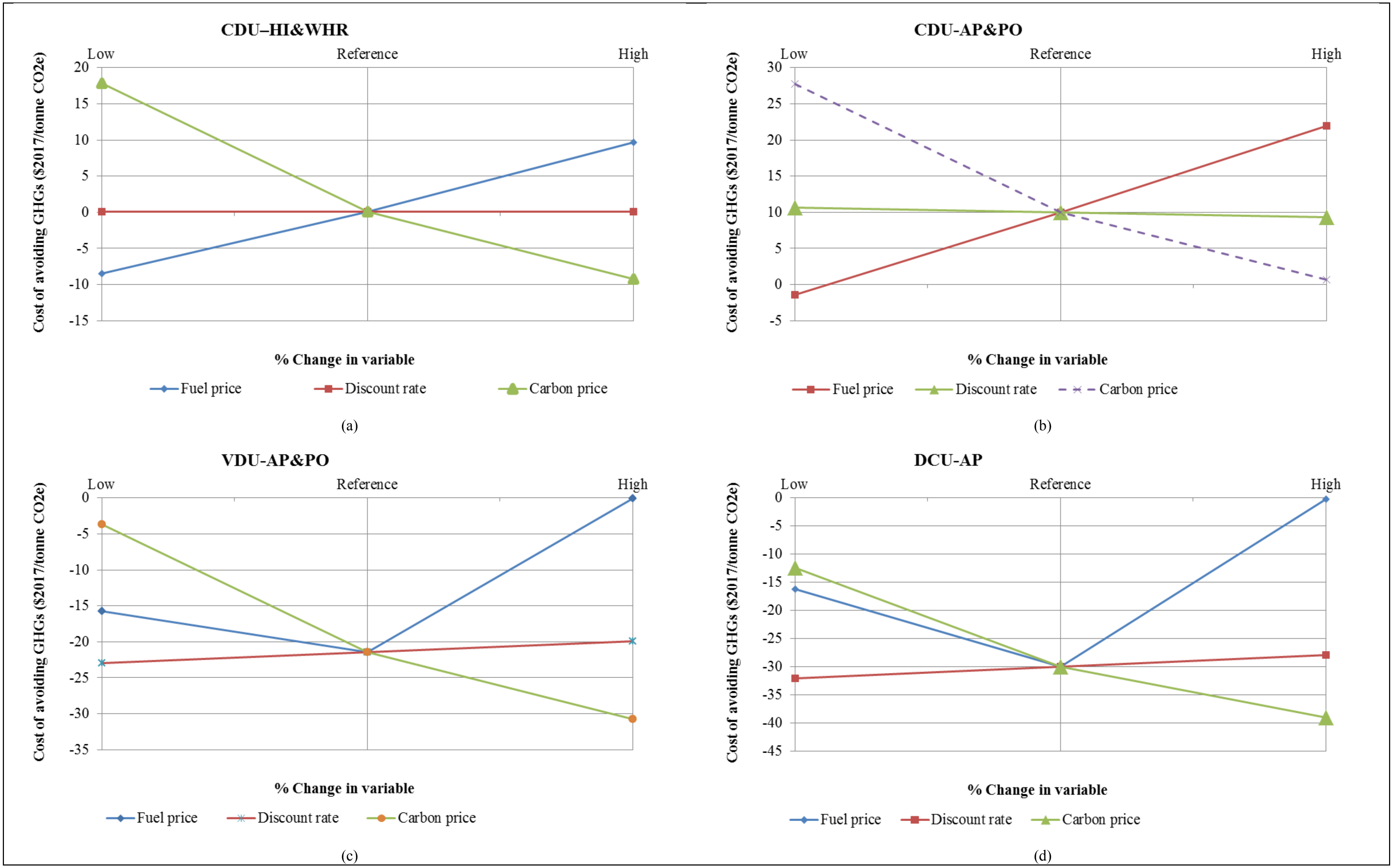
Figure D-7: Aspen HYSYS process flow diagram of (a) a base case alkylation unit and (b) a modified alkylation unit

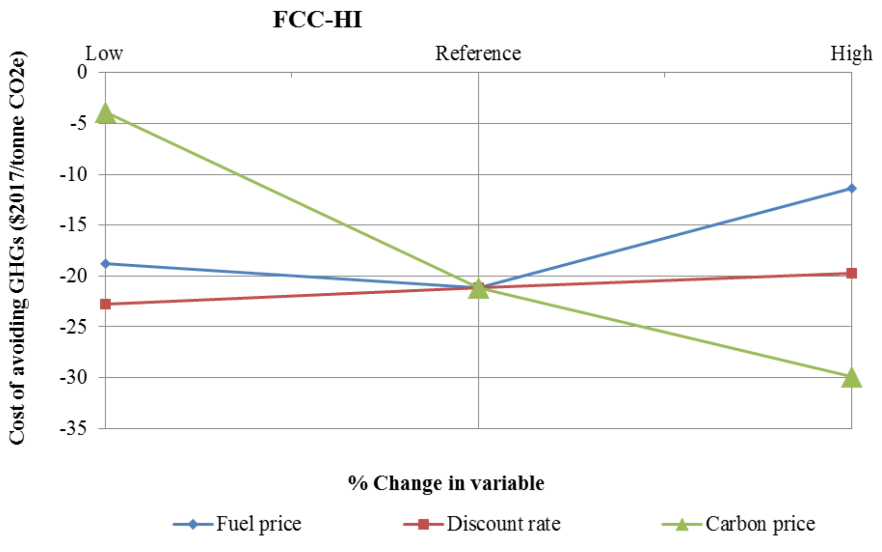
8.1.1.6. Pumps

Existing pump efficiency was assumed to be 75%. The installation of high efficiency motors and adjustable speed drives (ASD) that better match speed to load requirements for motor operations was assumed for energy loss reduction. An ASD is 11%-40% more efficient than a conventional pump. We assume an efficiency improvement of 11% in this study.

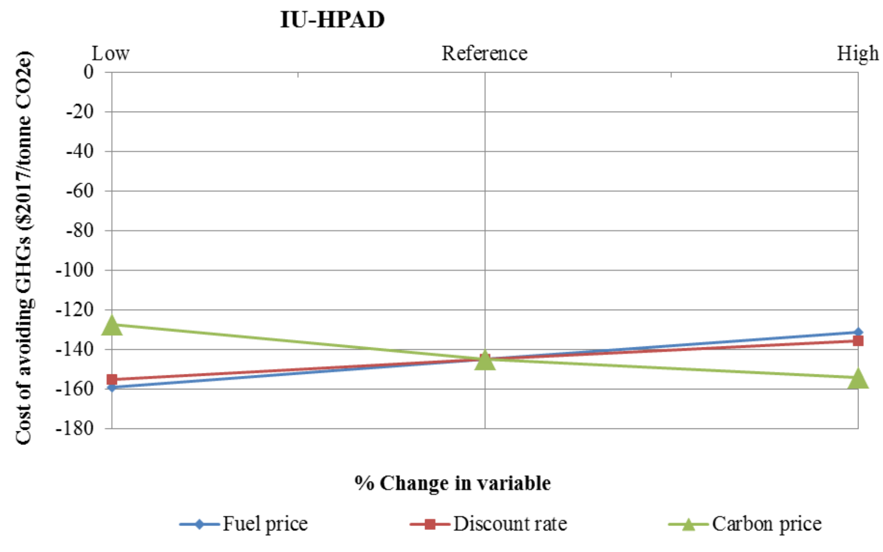
Appendix VI-II: Detail results of sensitivity analysis

Figure D-8: Sensitivity of the results to input parameters

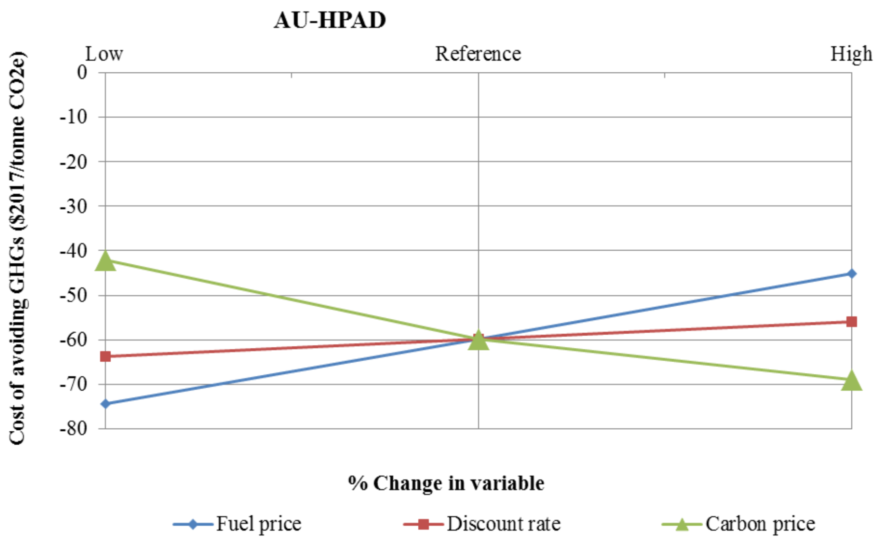



FCC-HI
Low
Reference
High
0
-5
-10
-15
-20
-25
-30
-35
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate
Carbon price

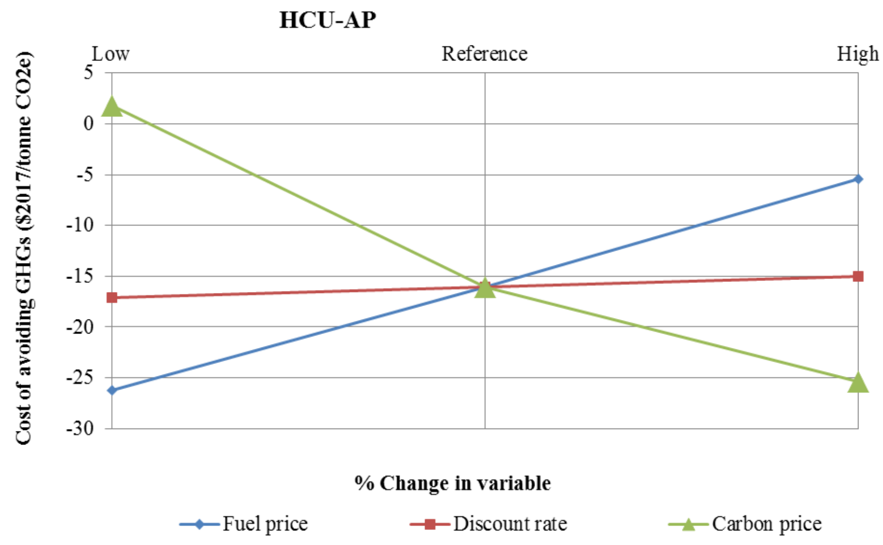
(e)


IU-HPAD
Low
Reference
High
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate
Carbon price

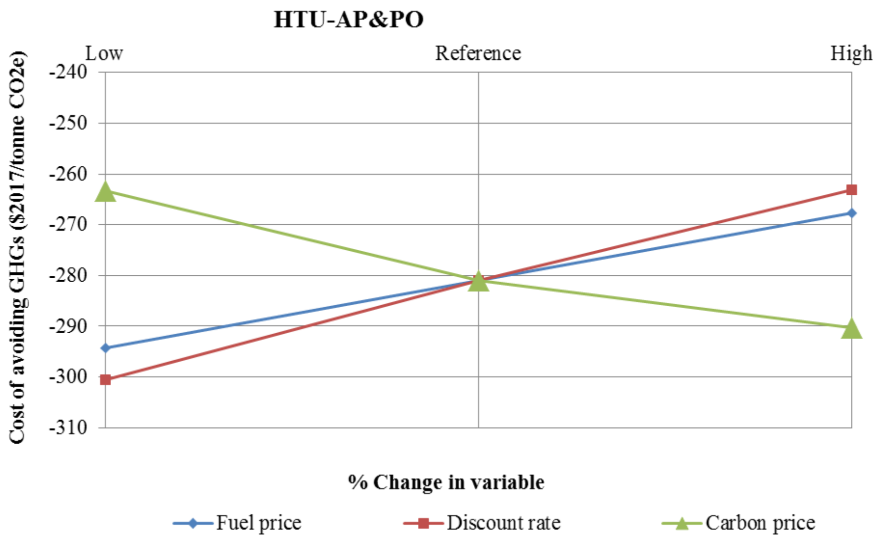
(f)


AU-HPAD
Low
Reference
High
0
-10
-20
-30
-40
-50
-60
-70
-80
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate
Carbon price

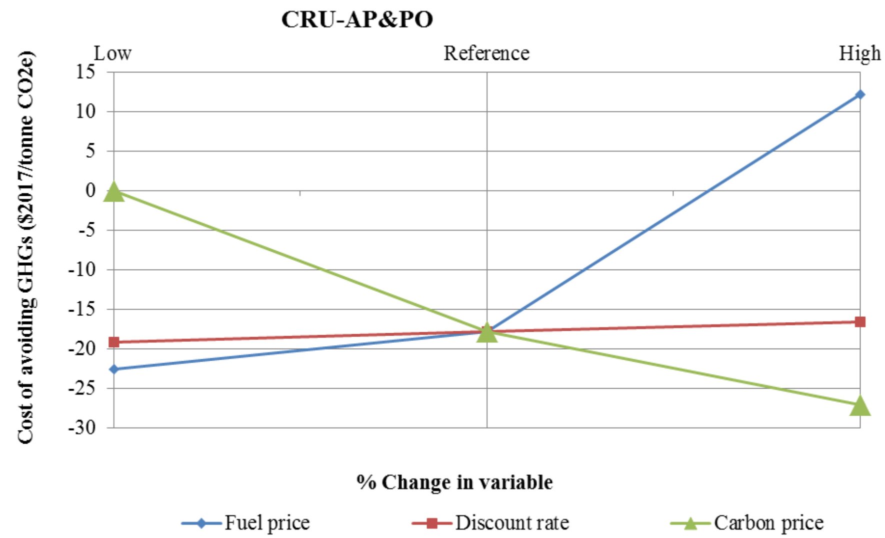
(g)


HCU-AP
Low
Reference
High
5
0
-5
-10
-15
-20
-25
-30
Cost of avoiding GHGs ($2017/tonne CO2e)
% Change in variable
Fuel price
Discount rate
Carbon price

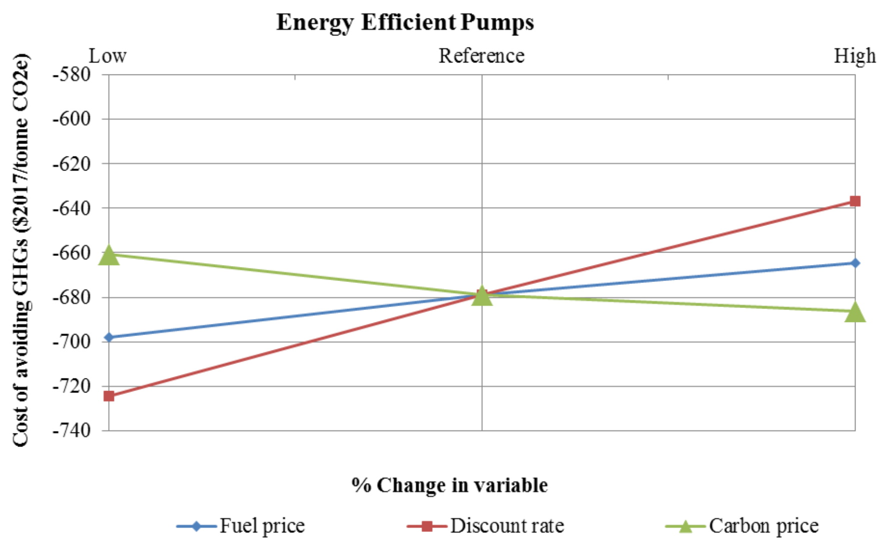
(h)


HTU-AP&PO
Low
Reference
High
Cost of avoiding GHGs ($2017/tonne CO2e)
-240
-250
-260
-270
-280
-290
-300
-310
% Change in variable
Fuel price
Discount rate
Carbon price

(i)


CRU-AP&PO
Low
Reference
High
Cost of avoiding GHGs ($2017/tonne CO2e)
15
10
5
0
-5
-10
-15
-20
-25
-30
% Change in variable
Fuel price
Discount rate
Carbon price

(j)


Energy Efficient Pumps
Low
Reference
High
Cost of avoiding GHGs ($2017/tonne CO2e)
-580
-600
-620
-640
-660
-680
-700
-720
-740
% Change in variable
Fuel price
Discount rate
Carbon price

(k)

Appendix V: Supplementary information for Chapter 6

Appendix V-I: Assumptions and input data for the analysis

SEC is a commonly used index to measure the energy intensity of a process. SEC measures the energy consumed to produce each unit of a final product. Depending on the considered boundary for the process and the choice of final or primary energy, the SEC of chemical products varies considerably. Of all the chemical products, ethylene, ammonia, and chlorine have the highest SECs (Appendix A-2 and A-3).

Table E-1: Input data for the Techno-economic model[33]

NO.	scenario name	Energy saving potential (GJ/tonne product)	Penetration rate by the end of 2030/2050 period (%)	Capital Cost of EE technology (CAD/tonne product)	Capital cost of existing technology (CAD/tonne product)	Changes in O&M (CAD/tonne product)
1	Adiabatic pre-reformer	1.03	90	15	0	0
2	Heat recovery from reformer flue gas	0.22	90	1	0	0
3	Low energy CO2 removal technologies	3.31	24	61	48	27
4	Autothermic non-constant pressure methanolizing-methanation process	1.13	38	49	39	0
5	Low temperature conversion technology	0.45	17.5	20	7	0
6	Unpowered ammonia recovery	0.5	41	2	1	0
7	Automatic control and optimization of ammonia synthesis reactor	0.65	43	1	1	0
8	Large-scale axial and radial ammonia synthesis tower	3.3	44	44	40	0
9	Combined cycle technology	2.3	38	49	39	0
10	Evaporative condenser cooling technology	0.09	27	3	1	0
11	synthesis gas molecular sieve dryer and direct synthesis converter feed	0.67	29	11	7	0
12	Energy integration (combined refrigeration)	1.17	90	1	0	0
13	High pressure combustion	1	40	12	0	0
14	Methanolization-hydrocarbylation purification technology	1.06	31	27	16	0

[33] All costs are in 2010 Canadian Dollar (CAD)

Table E-2: 1994 Estimated U.S. final energy consumption (HHV) for selected key chemicals[34] (including feedstock) [392]

Product	Final Energy Consumption (GJ/tonne)
Ethylene and co-products	67.5
Methanol	38.4
Polyethylene	9.3
Polypropylene	10.5
Polyvinyl chloride	11.6
Polystyrene	9.3
Nitrogen	1.8
Oxygen	1.8
Ammonia	39.8
Urea	2.8
Chlorine	19.2

Table E-3: Key chemical processes' energy consumption levels for selected countries (GJ/tonne-output) [437]

	World	USA	Canada	Germany	China	India
Steam cracking (high value chemicals)	16.9	18.3	18.3	15.7	16.7	16.7
Ammonia (including feedstock)	41.6	38	37.9	37.3	49.6	40.2
Methanol (excluding feedstock)	10.9	11.4	10	12.4	15	10.9
Chlorine	2.9	4.7	4.7	2.3	2.7	0.6
Soda ash (fuel and steam)	10.9	6.9	6.9	11.6	13.8	13.6
Soda ash (electricity)	0.2	0.0	0.0	0.3	0.2	0.3

Alberta has four major ethylene plants, two of which are among the largest in the world (see Appendix A-4) [396]. Ethylene is a key product in Alberta's petrochemical industry and is used to produce various petrochemical products such as polyethylene, glycol, ethylene oxide, alpha olefin, ethylene dichloride, benzene p xylene, and styrene. Ethylene production and demand are about 4 million tonnes (MT) per year in Alberta [397, 438].

[34] Similarities between the US' and Canada's chemical industry, both in terms of industry advancement and the feedstock used (mainly natural gas in North America), justify the comparability of the chemical sector's specific energy consumption (SEC) in the two countries (See Table A-3).

Table E-5: Production capacity of ethylene and its derivatives in Alberta [439]

Company	Location of plant	Product	Capacity (MT)
Dow Chemical	Fort Saskatchewan	Ethylene	1.304
Dow Chemical	Fort Saskatchewan	Polyethylene	0.848
Dow Chemical	Fort Saskatchewan	Ethylene dichloride	1.095
Dow Chemical	Prentiss	Polyethylene	0.5
MEGlobal Canada	Fort Saskatchewan	Ethylene glycol	0.34
MEGlobal Canada	Prentiss	Ethylene glycol	0.31
MEGlobal Canada	Prentiss	Ethylene glycol	0.35
NOVA Chemicals	Joffre	Ethylene	0.726
NOVA Chemicals	Joffre	Ethylene	0.817
NOVA & Dow Chemicals	Joffre	Ethylene	1.3
NOVA Chemicals	Joffre	Polyethylene	0.6
NOVA Chemicals	Joffre	Polyethylene	0.386
Shell Chemicals	Fort Saskatchewan	Ethylene glycol	0.45

Like the petrochemical sector, the fertilizer industry is a major sub-sector of Alberta's chemical industry. Of the nine fertilizer producers in Canada, six are located in Alberta (Appendix A-5). In general, fertilizers are classified in three categories: nitrogen fertilizers35 (N-Fertilizers), phosphate fertilizers36, and potassium (potash) fertilizers. The main fertilizer product in Alberta is the N-fertilizer (80-85%) (mainly ammonia and urea) [440]. No potash fertilizers are produced in the province [440].

Table E-6: Canada's major fertilizer producers and their products [397]

Company	Location	Ammonia	Urea	Nitric acid	Ammonia nitrate	Ammonium phosphate, sulphate
Agrium	Redwater, AB	×	×		×	×
Agrium	Fort Sask, AB	×	×	×		
Agrium	Carseland, AB	×	×			
Agrium	Joffre, AB	×				
Canadian Fertilizers	Medicine Hat, AB	×	×			
Orica	Carseland, AB			×	×	
Saskferco	Belle Plaine, SK	×	×			
Koch	Brandon, MB	×	×	×	×	×
Terra Industries	Courtight, ON	×	×	×	×	

[35]Urea; nitric acid; ammonia (liquid and aqueous); ammonium nitrate; ammonium sulphate.
[36]Phosphoric acid; ammonium phosphate; single superphosphate; triple superphosphate; sulphuric acid

References

[1] Intergovernmental Panel on Climate Change. 2018. About IPCC [Online]. Available: https://www.ipcc.ch/about/ Accessed [2019/01/04].
[2] United Nation Climate Change. 2018. About the Secretariat [Online]. Available: https://unfccc.int/about-us/about-the-secretariat Accessed [2019/01/04].
[3] United Nation Framework on Climate Change. 2018. The Kyoto Protocol [Online]. Available: https://unfccc.int/process/the-kyoto-protocol Accessed [2019/01/04].
[4] United Nations Framework Convention on Climate Change. 2018. The Paris Agreement [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement Accessed [2019/01/04].
[5] Fuss S, Canadell JG, Peters GP, al. e. Betting on negative emissions. Nature Climate Change. 2014;4:850.
[6] Rogelj J, Schaeffer M, Meinshausen M, Knutti R, Alcamo J, Riahi K, Hare W. Zero emission targets as long-term global goals for climate protection. Environmental Research Letters. 2015;10:105007.
[7] Working Group III of the Intergovernmental Panel on Climate Change. Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: editor.^editors. ed.: Cambridge Univ Press, Cambridge, UK; 2014. p.
[8] Millar RJ, Fuglestvedt JS, Friedlingstein P, al. e. Emission budgets and pathways consistent with limiting warming to 1.5 ^{0}C. Nature Geoscience. 2017;10:741.
[9] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, . . . Kriegler E. Mitigation pathways compatible with 1.5 C in the context of sustainable development. 2018.
[10] International Energy Agency. 2018. Tracking clean energy progress in industrial sector [Online]. Available: https://www.iea.org/tcep/industry/ Accessed [2019/01/03].
[11] Change IPoC. Climate change 2014: Mitigation of climate change. ed.: Cambridge University Press; 2015.
[12] Edelenbosch OY, Kermeli K, Crijns-Graus W, Worrell E, Bibas R, Fais B, . . . van Vuuren DP. Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. Energy. 2017;122:701-710.
[13] Saygin D. Assessing industrial energy use and CO2 emissions: Opportunities for energy efficiency, biomass and CCS. 2012.
[14] International Energy Agency. Energy Technology Perspectives 2012—Pathways to a Clean Energy System. In: editor.^editors. ed.: International Energy Agency Paris; 2012. p.
[15] Intergovernmental panel on climate change. 2018. Special report: Global warming of 1.5^{0}C [Online]. Available: https://www.ipcc.ch/sr15/ Accessed [2018-12-20].
[16] Agency IE. Energy Efficiency 2018. ed.: 2018.
[17] World Business Council for Sustainable Development. 2018. Cement Sustainability Initiative [Online]. Available: http://www.wbcsdcement.org/ Accessed [03/01/2019].
[18] Insitute for Industrial Productivity. 2018. Ultra-Low CO2 Steelmaking (ULCOS) [Online]. Available: http://ietd.iipnetwork.org/content/ultra-low-co2-steelmaking Accessed [03/01/2019].
[19] Worrell E, Bernstein L, Roy J, Price L, Harnisch J. Industrial energy efficiency and climate change mitigation. Energy efficiency. 2009;2:109.
[20] Tahouni N, Gholami M, Panjeshahi MH. Integration of flare gas with fuel gas network in refineries. Energy. 2016;111:82-91.

[21] Jagannath A, Hasan MMF, Al-Fadhli FM, Karimi IA, Allen DT. Minimize flaring through integration with fuel gas networks. Industrial & Engineering Chemistry Research. 2012;51:12630-12641.
[22] Plesu V, Bumbac G, Iancu P, Ivanescu I, Popescu DC. Thermal coupling between crude distillation and delayed coking units. Applied thermal engineering. 2003;23:1857-1869.
[23] Hasanbeigi A, Morrow W, Sathaye J, Masanet E, Xu T. A bottom-up model to estimate the energy efficiency improvement and CO_2 emission reduction potentials in the Chinese iron and steel industry. Energy. 2013;50:315-325.
[24] Brunke J-C, Blesl M. A plant-specific bottom-up approach for assessing the cost-effective energy conservation potential and its ability to compensate rising energy-related costs in the German iron and steel industry. Energy Policy. 2014;67:431-446.
[25] Pardo N, Moya JA. Prospective scenarios on energy efficiency and CO< sub> 2</sub> emissions in the European iron & steel industry. Energy. 2013;54:113-128.
[26] Madlool N, Saidur R, Hossain M, Rahim N. A critical review on energy use and savings in the cement industries. Renewable and Sustainable Energy Reviews. 2011;15:2042-2060.
[27] Schneider M, Romer M, Tschudin M, Bolio H. Sustainable cement production—present and future. Cement and Concrete Research. 2011;41:642-650.
[28] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. Renewable and Sustainable Energy Reviews. 2011;15:150-168.
[29] Doheim MA, Sayed SA, Hamed OA. Energy analysis and waste heat recovery in a refinery. Energy. 1986;11:691-696.
[30] Sharaf Eldean MA, Soliman AM. A novel study of using oil refinery plants waste gases for thermal desalination and electric power generation: Energy, exergy & cost evaluations. Applied Energy. 2017;195:453-477.
[31] Al-Rowaili FN, Ba-Shammakh MS. Maximisation of an oil refinery profit with products quality and NO2 constraints. Journal of Cleaner Production. 2017;165:1582-1597.
[32] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy. 2010;87:1059-1082.
[33] Hall LMH, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Applied Energy. 2016;169:607-628.
[34] Suganthi L, Samuel AA. Energy models for demand forecasting—A review. Renewable and Sustainable Energy Reviews. 2012;16:1223-1240.
[35] Timmerman J, Vandevelde L, Van Eetvelde G. Towards low carbon business park energy systems: Classification of techno-economic energy models. Energy. 2014;75:68-80.
[36] Rao S, Riahi K. The role of Non-CO_3 greenhouse gases in climate change mitigation: long-term scenarios for the 21st Century. The Energy Journal. 2006:177-200.
[37] Shafiei E, Saboohi Y, Ghofrani MB. Impact of innovation programs on development of energy system: Case of Iranian electricity-supply system. Energy Policy. 2009;37:2221-2230.
[38] Kannan R. The development and application of a temporal MARKAL energy system model using flexible time slicing. Applied Energy. 2011;88:2261-2272.
[39] Cosmi C, Macchiato M, Mangiamele L, Marmo G, Pietrapertosa F, Salvia M. Environmental and economic effects of renewable energy sources use on a local case study. Energy Policy. 2003;31:443-457.
[40] Kannan R, Turton H. A long-term electricity dispatch model with the TIMES framework. Environmental Modeling & Assessment. 2013;18:325-343.

[41] Comodi G, Cioccolanti L, Gargiulo M. Municipal scale scenario: analysis of an Italian seaside town with MarkAL-TIMES. Energy Policy. 2012;41:303-315.
[42] Vaillancourt K, Labriet M, Loulou R, Waaub J-P. The role of nuclear energy in long-term climate scenarios: An analysis with the World-TIMES model. Energy Policy. 2008;36:2296-2307.
[43] Contaldi M, Gracceva F, Mattucci A. Hydrogen perspectives in Italy: analysis of possible deployment scenarios. International Journal of Hydrogen Energy. 2008;33:1630-1642.
[44] Contreras A, Guervós E, Posso F. Market penetration analysis of the use of hydrogen in the road transport sector of the Madrid region, using MARKAL. International Journal of Hydrogen Energy. 2009;34:13-20.
[45] Nguyen KQ. Impacts of wind power generation and CO 2 emission constraints on the future choice of fuels and technologies in the power sector of Vietnam. Energy Policy. 2007;35:2305-2312.
[46] Thevenard D, Leng G, Martel S. The RETScreen model for assessing potential PV projects. In: editor.^editors. Photovoltaic Specialists Conference, 2000 Conference Record of the Twenty-Eighth IEEE. ed.: IEEE; 2000. p. 1626-1629.
[47] Mirzahosseini AH, Taheri T. Environmental, technical and financial feasibility study of solar power plants by RETScreen, according to the targeting of energy subsidies in Iran. Renewable and Sustainable Energy Reviews. 2012;16:2806-2811.
[48] Lee K-H, Lee D-W, Baek N-C, Kwon H-M, Lee C-J. Preliminary determination of optimal size for renewable energy resources in buildings using RETScreen. Energy. 2012;47:83-96.
[49] Zhou Y, Clarke L, Eom J, Kyle P, Patel P, Kim SH, . . . Seiple T. Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. Applied Energy. 2014;113:1077-1088.
[50] Ozturk HK, Canyurt OE, Hepbasli A, Utlu Z. Residential-commercial energy input estimation based on genetic algorithm (GA) approaches: an application of Turkey. Energy and Buildings. 2004;36:175-183.
[51] Kannan R, Strachan N. Modelling the UK residential energy sector under long-term decarbonisation scenarios: Comparison between energy systems and sectoral modelling approaches. Applied Energy. 2009;86:416-428.
[52] Pietzcker RC, Longden T, Chen W, Fu S, Kriegler E, Kyle P, Luderer G. Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. Energy. 2014;64:95-108.
[53] Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews. 2009;13:1819-1835.
[54] Siller T, Kost M, Imboden D. Long-term energy savings and greenhouse gas emission reductions in the Swiss residential sector. Energy Policy. 2007;35:529-539.
[55] Balaras CA, Gaglia AG, Georgopoulou E, Mirasgedis S, Sarafidis Y, Lalas DP. European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. Building and environment. 2007;42:1298-1314.
[56] Wang C, Cai W, Lu X, Chen J. CO2 mitigation scenarios in China’s road transport sector. Energy Conversion and Management. 2007;48:2110-2118.

[57] Yang C, McCollum D, McCarthy R, Leighty W. Meeting an 80% reduction in greenhouse gas emissions from transportation by 2050: A case study in California. Transportation Research Part D: Transport and Environment. 2009;14:147-156.
[58] McCollum D, Yang C. Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications. Energy Policy. 2009;37:5580-5596.
[59] Cai W, Wang C, Chen J, Wang K, Zhang Y, Lu X. Comparison of CO2 emission scenarios and mitigation opportunities in China's five sectors in 2020. Energy Policy. 2008;36:1181-1194.
[60] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy. 2009;34:524-531.
[61] Davis M, Ahiduzzaman M, Kumar A. Mapping Canadian energy flow from primary fuel to end use. Energy Conversion and Management. 2018;156:178-191.
[62] Subramanyam V, Kumar A, Talaei A, Mondal MAH. Energy efficiency improvement opportunities and associated greenhouse gas abatement costs for the residential sector. Energy. 2017;118:795-807.
[63] Subramanyam V, Ahiduzzaman M, Kumar A. Greenhouse gas emissions mitigation potential in the commercial and institutional sector. Energy and Buildings. 2017;140:295-304.
[64] Hong S, Chung Y, Kim J, Chun D. Analysis on the level of contribution to the national greenhouse gas reduction target in Korean transportation sector using LEAP model. Renewable and Sustainable Energy Reviews. 2016;60:549-559.
[65] Davis M, Ahiduzzaman M, Kumar A. How will Canada's greenhouse gas emissions change by 2050? A disaggregated analysis of past and future greenhouse gas emissions using bottom-up energy modelling and Sankey diagrams. Applied Energy. 2018;220:754-786.
[66] Davis M. The Development of a Technology-Explicit Bottom-Up Integrated Multi-Regional Energy Model of Canada. In: editor.^editors. ed.: 2017. p.
[67] van Vuuren DP, Hoogwijk M, Barker T, Riahi K, Boeters S, Chateau J, . . . Blok K. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. Energy Policy. 2009;37:5125-5139.
[68] Nakata T, Silva D, Rodionov M. Application of energy system models for designing a low-carbon society. Progress in Energy and Combustion Science. 2011;37:462-502.
[69] Khan SI, Islam A, Khan AH. Energy Forecasting of Bangladesh in Gas Sector Using LEAP Software. Global Journal of Research In Engineering. 2011;11.
[70] Huang Y, Bor YJ, Peng C-Y. The long-term forecast of Taiwan's energy supply and demand: LEAP model application. Energy Policy. 2011;39:6790-6803.
[71] Shabbir R, Ahmad SS. Monitoring urban transport air pollution and energy demand in Rawalpindi and Islamabad using leap model. Energy. 2010;35:2323-2332.
[72] Hejazi M, Edmonds J, Clarke L, Kyle P, Davies E, Chaturvedi V, . . . Kim S. Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. Technological Forecasting and Social Change. 2014;81:205-226.
[73] Mounir ZM, Ma CM, Amadou I. Application of Water Evaluation and Planning (WEAP): a model to assess future water demands in the Niger River (In Niger Republic). Modern Applied Science. 2011;5:38.
[74] Lévite H, Sally H, Cour J. Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model. Physics and Chemistry of the Earth, Parts A/B/C. 2003;28:779-786.

[75] Wise M, Calvin K, Kyle P, Luckow P, Edmonds J. Economic and physical modeling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. Climate Change Economics. 2014;5:1450003.
[76] Calvin K, Wise M, Clarke L, Edmonds J, Kyle P, Luckow P, Thomson A. Implications of simultaneously mitigating and adapting to climate change: initial experiments using GCAM. Climatic Change. 2013;117:545-560.
[77] Edmonds JA, Wise M, MacCracken C. Advanced energy technologies and climate change: An analysis using the global change assessment model (GCAM). In: editor.^editors. ed.: Pacific Northwest National Lab.(PNNL), Richland, WA (United States); 1994. p.
[78] Mishra GS, Kyle P, Teter J, Morrison GM, Kim S, Yeh S. Transportation module of global change assessment model (GCAM): model documentation. In: editor.^editors. ed.: 2013. p.
[79] Talaei A, Pier D, Iyer AV, Ahiduzzaman M, Kumar A. Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation options for the cement industry. Energy. 2019;170:1051-1066.
[80] Talaei A, Ahiduzzaman M, Kumar A. Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation potentials in the chemical sector. Energy. 2018;153:231-247.
[81] Fleiter T, Worrell E, Eichhammer W. Barriers to energy efficiency in industrial bottom-up energy demand models—a review. Renewable and Sustainable Energy Reviews. 2011;15:3099-3111.
[82] Song H-J, Lee S, Maken S, Ahn S-W, Park J-W, Min B, Koh W. Environmental and economic assessment of the chemical absorption process in Korea using the LEAP model. Energy Policy. 2007;35:5109-5116.
[83] Hasanbeigi A, Jiang Z, Price L. 2013. Analysis of the past and future trends of energy use in key medium and large-sized Chinese steel enterprises, 2000-2030 [Online]. Ernest Orlando Lawrence Berkeley National Laboratory. Available: https://china.lbl.gov/publications/analysis-past-and-future-trends Accessed 24/08/2017].
[84] Yan X, Crookes RJ. Reduction potentials of energy demand and GHG emissions in China's road transport sector. Energy Policy. 2009;37:658-668.
[85] Manzini F. Inserting renewable fuels and technologies for transport in Mexico City Metropolitan Area. International Journal of Hydrogen Energy. 2006;31:327-335.
[86] Pradhan S, Ale BB, Amatya VB. Mitigation potential of greenhouse gas emission and implications on fuel consumption due to clean energy vehicles as public passenger transport in Kathmandu Valley of Nepal: a case study of trolley buses in ring road. Energy. 2006;31:1748-1760.
[87] Li J. Towards a low-carbon future in China's building sector—A review of energy and climate models forecast. Energy Policy. 2008;36:1736-1747.
[88] Davoudpour H, Ahadi MS. The potential for greenhouse gases mitigation in household sector of Iran: cases of price reform/efficiency improvement and scenario for 2000–2010. Energy Policy. 2006;34:40-49.
[89] Giatrakos GP, Tsoutsos TD, Zografakis N. Sustainable power planning for the island of Crete. Energy Policy. 2009;37:1222-1238.
[90] Islas J, Manzini F, Martínez M. Renewable energies in electricity generation for reduction of greenhouse gases in Mexico 2025. AMBIO: A Journal of the Human Environment. 2002;31:35-39.

[91] Cai W, Wang C, Wang K, Zhang Y, Chen J. Scenario analysis on CO 2 emissions reduction potential in China's electricity sector. Energy Policy. 2007;35:6445-6456.
[92] Gonzalez-Salazar MA, Venturini M, Poganietz W-R, Finkenrath M, Kirsten T, Acevedo H. 2014. Bioenergy technology roadmap for Colombia [Online]. Available: http://eprints.unife.it/774/1/Bioenergy_technology_roadmap_for_Colombia.pdf Accessed 07/21/2017].
[93] Asia Pacific Energy Research Center. 2009. Energy demand and supply outlook 4th edition. [Online]. Available: http://aperc.ieej.or.jp/publications/reports/outlook.php Accessed].
[94] Lazarus M, Erickson P, Chandler C, Daudon M, Donegan S, Gallivan F, Ang-Olson J. 2011. Getting to zero: a pathway to a carbon neutral Seattle [Online]. Available: https://www.seattle.gov/Documents/Departments/OSE/CN_Seattle_Report_May_2011.pdf Accessed 17/04/2017].
[95] Erickson P, Heaps C, Lazarus M. Greenhouse gas mitigation in developing countries. Stockholm Environment Institute. 2009.
[96] Kumar A, Bhattacharya S, Pham H-L. Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the long range energy alternative planning system model. Energy. 2003;28:627-654.
[97] Jebaraj S, Iniyan S. A review of energy models. Renewable and Sustainable Energy Reviews. 2006;10:281-311.
[98] Jun S, Lee S, Park J-W, Jeong S-J, Shin H-C. The assessment of renewable energy planning on CO 2 abatement in South Korea. Renewable Energy. 2010;35:471-477.
[99] Amirnekooei K, Ardehali M, Sadri A. Integrated resource planning for Iran: Development of reference energy system, forecast, and long-term energy-environment plan. Energy. 2012;46:374-385.
[100] Government of Canada. 2017. Global greenhouse gas emissions [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/global-greenhouse-gas-emissions.html Accessed [30/01/2018].
[101] Government of Canada. 2016. Pan-Canadian Framework on Clean Growth and Climate Change [Online]. Available: https://www.canada.ca/content/dam/themes/environment/documents/weather1/20170125-en.pdf Accessed [05/25/2017].
[102] Kesicki F, Yanagisawa A. Modelling the potential for industrial energy efficiency in IEA's World Energy Outlook. Energy efficiency. 2015;8:155-169.
[103] International Energy Agency. 2018. Insights Series 2018 - Energy Efficiency Potential in Canada [Online]. Available: https://webstore.iea.org/insights-series-2018-energy-efficiency-potential-in-canada Accessed [04/01/2019].
[104] Government of Canada. 2018. The Paris Agreement [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/paris-agreement.html Accessed [2018/09/17].
[105] Bataille C, Åhman M, Neuhoff K, Nilsson LJ, Fischedick M, Lechtenböhmer S, . . . Waisman H. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement. Journal of Cleaner Production. 2018.
[106] Natural Resources Canada Office of Energy Efficiency. 2018. Comprehensive energy use database, 1990 to 2015 [Online]. Available:

http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_agg_ab.cfm Accessed [05/04/2017].
[107] Statistics Canada. 2018. Statistics by subject – Energy [Online]. Available: https://www.statcan.gc.ca/eng/subjects/Energy Accessed [05/04/2018].
[108] National Energy Board. 2019. Data hub [Online]. Available: https://www.neb-one.gc.ca/rsrccntr/dthb/index-eng.html Accessed [04/01/2019].
[109] Canadian Energy and Emissions Data Center 2019. CEEDC Database on Energy, Production and Intensity Indicators for Canadian Industry [Online]. Available: https://cieedacdb.rem.sfu.ca/naics-database/ Accessed [04/01/2019].
[110] Organisation for Economic Co-operation and Development. 2018. Energy Statistics of OECD Countries [Online]. Available: https://www.oecd-ilibrary.org/energy/energy-statistics-of-oecd-countries_19962827-en Accessed [04/01/2019].
[111] Canadian Steel Producers Association. 2007. Benchmarking energy intensity in the Canadian steel industry [Online]. Available: http://198.103.48.133/industrial/technical-info/benchmarking/csi/documents/SteelBenchmarkEnglish.pdf Accessed [24/08/2017].
[112] Natural Resource Canada. 2008. Canadian Ammonia Producers: Benchmarking energy efficiency and carbon dioxide emissions [Online]. Ottawa, Canada. Available: http://www.nrcan.gc.ca/sites/oee.nrcan.gc.ca/files/files/pdf/industrial/ammonia-study.pdf Accessed].
[113] Natural Resource Canada. 2009. Canadian Cement Industry Energy Benchmarking [Online]. Available: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/Publications/industrial/cement-eng.pdf Accessed].
[114] Natural Resources Canada. 2001. Energy consumption benchmark guide: Cement clinker production [Online]. Available: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/publications/industrial/BenchmCement_e.pdf Accessed [04/10/2017].
[115] Executive Office of the President of the United States. 2017. North Amercian industrty classificaiton system [Online]. Available: https://www.census.gov/eos/www/naics/2017NAICS/2017_NAICS_Manual.pdf Accessed].
[116] United Nation Framework Convenion on Climate Change. 2015. The Paris Agreement [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement Accessed 2018-12-04].
[117] Wang H, Chen W. Modelling deep decarbonization of industrial energy consumption under 2-degree target: Comparing China, India and Western Europe. Applied Energy. 2019;238:1563-1572.
[118] International Energy Agency. 2007. Tracking industrial energy efficiency and CO_2 emissions [Online]. Paris, France.: International Energy Agency. Available: https://www.iea.org/publications/freepublications/publication/tracking_emissions.pdf Accessed 24/08/2017].
[119] Environment and Climate Change Canada. 2017. Canadian environmental sustainability indicators: Greenhouse gas emissions [Online]. Available: https://www.ec.gc.ca/indicateurs-indicators/FBF8455E-66C1-4691-9333-5D304E66918D/GHGEmissions_EN.pdf Accessed 30/01/2018].

[120] Talaei A, Ahiduzzaman M, A K. Long-term energy efficiency improvement and greenhouse gas emission mitigation in the iron and steel industry: A case study of Canada. In: editor.^editors. ed.: 2018. p.
[121] Ang BW. The LMDI approach to decomposition analysis: a practical guide. Energy Policy. 2005;33:867-871.
[122] Ang BW. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy. 2004;32:1131-1139.
[123] Zhao X, Ma C, Hong D. Why did China's energy intensity increase during 1998–2006: decomposition and policy analysis. Energy Policy. 2010;38:1379-1388.
[124] Hammond GP, Norman JB. Decomposition analysis of energy-related carbon emissions from UK manufacturing. Energy. 2012;41:220-227.
[125] Zhao M, Tan L, Zhang W, Ji M, Liu Y, Yu L. Decomposing the influencing factors of industrial carbon emissions in Shanghai using the LMDI method. Energy. 2010;35:2505-2510.
[126] Hasanbeigi A, de la Rue du Can S, Sathaye J. Analysis and decomposition of the energy intensity of California industries. Energy Policy. 2012;46:234-245.
[127] Liu L-C, Fan Y, Wu G, Wei Y-M. Using LMDI method to analyze the change of China's industrial CO_2 emissions from final fuel use: An empirical analysis. Energy Policy. 2007;35:5892-5900.
[128] Jeong K, Kim S. LMDI decomposition analysis of greenhouse gas emissions in the Korean manufacturing sector. Energy Policy. 2013;62:1245-1253.
[129] Akbostancı E, Tunç Gİ, Türüt-Aşık S. CO2 emissions of Turkish manufacturing industry: a decomposition analysis. Applied Energy. 2011;88:2273-2278.
[130] Diakoulaki D, Mandaraka M. Decomposition analysis for assessing the progress in decoupling industrial growth from CO2 emissions in the EU manufacturing sector. Energy Economics. 2007;29:636-664.
[131] Torvanger A. Manufacturing sector carbon dioxide emissions in nine OECD countries, 1973–87: A Divisia index decomposition to changes in fuel mix, emission coefficients, industry structure, energy intensities and international structure. Energy Economics. 1991;13:168-186.
[132] Kim Y, Worrell E. International comparison of CO_2 emission trends in the iron and steel industry. Energy Policy. 2002;30:827-838.
[133] Wang B, Cui C, Li Z. Influence factors and forecast of carbon emission in China: structure adjustment for emission peak. In: editor.^editors. IOP Conference Series: Earth and Environmental Science. ed.: IOP Publishing; 2018. p. 012197.
[134] Zhang J, Wang C-m, Liu L, Guo H, Liu G-d, Li Y-w, Deng S-h. Investigation of carbon dioxide emission in China by primary component analysis. Science of The Total Environment. 2014;472:239-247.
[135] Xia XH, Huang GT, Chen GQ, Zhang B, Chen ZM, Yang Q. Energy security, efficiency and carbon emission of Chinese industry. Energy Policy. 2011;39:3520-3528.
[136] Sun W, Sun J. Prediction of carbon dioxide emissions based on principal component analysis with regularized extreme learning machine: The case of China. Environmental Engineering Research. 2017;22:302-311.
[137] Antanasijević DZ, Ristić MĐ, Perić-Grujić AA, Pocajt VV. Forecasting GHG emissions using an optimized artificial neural network model based on correlation and principal component analysis. International Journal of Greenhouse Gas Control. 2014;20:244-253.
[138] Su B, Ang BW, Low M. Input–output analysis of CO2 emissions embodied in trade and the driving forces: Processing and normal exports. Ecological Economics. 2013;88:119-125.

[139] Wiedmann T. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological Economics. 2009;69:211-222.
[140] Chang YF, Lewis C, Lin SJ. Comprehensive evaluation of industrial CO_2 emission (1989–2004) in Taiwan by input–output structural decomposition. Energy Policy. 2008;36:2471-2480.
[141] Guan D, Hubacek K, Weber CL, Peters GP, Reiner DM. The drivers of Chinese CO2 emissions from 1980 to 2030. Global Environmental Change. 2008;18:626-634.
[142] Wood R. Structural decomposition analysis of Australia's greenhouse gas emissions. Energy Policy. 2009;37:4943-4948.
[143] Su B, Ang BW. Structural decomposition analysis applied to energy and emissions: some methodological developments. Energy Economics. 2012;34:177-188.
[144] Ang BW. 2016. A simple guide to tLMDI decompositon analysis [Online]. Department of Industrials and System Engineering, National University of Singapore, Singapore. Available: https://www.isem.nus.edu.sg/staff/angbw/pdf/A_Simple_Guide_to_LMDI.pdf Accessed 23/03/2018].
[145] Donglan Z, Dequn Z, Peng Z. Driving forces of residential CO_2 emissions in urban and rural China: An index decomposition analysis. Energy Policy. 2010;38:3377-3383.
[146] Zhang C, Su B, Zhou K, Yang S. Analysis of electricity consumption in China (1990–2016) using index decomposition and decoupling approach. Journal of Cleaner Production. 2019;209:224-235.
[147] Wang S, Zhu X, Song D, Wen Z, Chen B, Feng K. Drivers of CO2 emissions from power generation in China based on modified structural decomposition analysis. Journal of Cleaner Production. 2019;220:1143-1155.
[148] Zhang M, Li H, Zhou M, Mu H. Decomposition analysis of energy consumption in Chinese transportation sector. Applied Energy. 2011;88:2279-2285.
[149] Lu I, Lin SJ, Lewis C. Decomposition and decoupling effects of carbon dioxide emission from highway transportation in Taiwan, Germany, Japan and South Korea. Energy Policy. 2007;35:3226-3235.
[150] Xu J-H, Fleiter T, Eichhammer W, Fan Y. Energy consumption and CO_2 emissions in China's cement industry: A perspective from LMDI decomposition analysis. Energy Policy. 2012;50:821-832.
[151] Wang Y, Zhu Q, Geng Y. Trajectory and driving factors for GHG emissions in the Chinese cement industry. Journal of Cleaner Production. 2013;53:252-260.
[152] Lin B, Zhang Z. Carbon emissions in China′s cement industry: A sector and policy analysis. Renewable and Sustainable Energy Reviews. 2016;58:1387-1394.
[153] Hasanbeigi A, Jiang Z, Price L. Retrospective and prospective analysis of the trends of energy use in Chinese iron and steel industry. Journal of Cleaner Production. 2014;74:105-118.
[154] Sheinbaum C, Ozawa L, Castillo D. Using logarithmic mean Divisia index to analyze changes in energy use and carbon dioxide emissions in Mexico's iron and steel industry. Energy Economics. 2010;32:1337-1344.
[155] Song Y, Huang J-B, Feng C. Decomposition of energy-related CO_2 emissions in China's iron and steel industry: A comprehensive decomposition framework. Resources Policy. 2018.
[156] Lin B, Moubarak M. Decomposition analysis: Change of carbon dioxide emissions in the Chinese textile industry. Renewable and Sustainable Energy Reviews. 2013;26:389-396.
[157] Du Z, Lin B. Analysis of carbon emissions reduction of China's metallurgical industry. Journal of Cleaner Production. 2018;176:1177-1184.

[158] Paul S, Bhattacharya RN. CO 2 emission from energy use in India: a decomposition analysis. Energy Policy. 2004;32:585-593.
[159] Zhang M, Mu H, Ning Y, Song Y. Decomposition of energy-related CO2 emission over 1991–2006 in China. Ecological Economics. 2009;68:2122-2128.
[160] Wang C, Chen J, Zou J. Decomposition of energy-related CO_2 emission in China: 1957–2000. Energy. 2005;30:73-83.
[161] Hatzigeorgiou E, Polatidis H, Haralambopoulos D. CO_2 emissions in Greece for 1990–2002: A decomposition analysis and comparison of results using the Arithmetic Mean Divisia Index and Logarithmic Mean Divisia Index techniques. Energy. 2008;33:492-499.
[162] Xu S-C, He Z-X, Long R-Y. Factors that influence carbon emissions due to energy consumption in China: Decomposition analysis using LMDI. Applied Energy. 2014;127:182-193.
[163] Andreoni V, Galmarini S. Decoupling economic growth from carbon dioxide emissions: A decomposition analysis of Italian energy consumption. Energy. 2012;44:682-691.
[164] Ma C, Stern DI. China's changing energy intensity trend: A decomposition analysis. Energy Economics. 2008;30:1037-1053.
[165] İpek Tunç G, Türüt-Aşık S, Akbostancı E. A decomposition analysis of CO_2 emissions from energy use: Turkish case. Energy Policy. 2009;37:4689-4699.
[166] Lin B, Ouyang X. Analysis of energy-related CO_2 (carbon dioxide) emissions and reduction potential in the Chinese non-metallic mineral products industry. Energy. 2014;68:688-697.
[167] Wang J, Hu M, Rodrigues JFD. An empirical spatiotemporal decomposition analysis of carbon intensity in China's industrial sector. Journal of Cleaner Production. 2018;195:133-144.
[168] Shahiduzzaman M, Alam K. Changes in energy efficiency in Australia: A decomposition of aggregate energy intensity using logarithmic mean Divisia approach. Energy Policy. 2013;56:341-351.
[169] Huang J-p. Industry energy use and structural change: A case study of The People's Republic of China. Energy Economics. 1993;15:131-136.
[170] Liu L-C, Fan Y, Wu G, Wei Y-M. Using LMDI method to analyze the change of China's industrial CO 2 emissions from final fuel use: an empirical analysis. Energy Policy. 2007;35:5892-5900.
[171] Worrell E, Price L, Martin N, Farla J, Schaeffer R. Energy intensity in the iron and steel industry: a comparison of physical and economic indicators. Energy Policy. 1997;25:727-744.
[172] Statistics Canada. 2018. North American Industry Classification System (NAICS) Canada 2017 Version 2.0 [Online]. Available: http://www23.statcan.gc.ca/imdb/p3VD.pl?Function=getVD&TVD=380372 Accessed 01/02/2018].
[173] Natural Resources Canada. 2018. Electricity geneation GHG emissions by energy source [Online]. Available: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=HB&sector=egen&juris=00&rn=2&page=4&CFID=1829105&CFTOKEN=4c86e90f21df0894-7A0C3B89-A20D-6DB3-06FB58AD1E493718 Accessed 02/04/2018].
[174] Canadian Energy and Emissions Data Centre. 2018. Energy, Production and Intensity Indicators for Canadian Industry [Online]. Available: http://www.sfu.ca/ceedc/databases.html Accessed 05/04/2018].

[175] Build Force Canada. 2018. Construction Canada factsheet [Online]. Available: http://www.buildforce.ca/en/media/facts Accessed 2018-11-06].
[176] Bogdanski BE. The rise and fall of the Canadian pulp and paper sector. The Forestry Chronicle. 2014;90:785-793.
[177] Government of Quebec. 2018. Clean Air Regulation-Environment Quality Act [Online]. Available: http://legisquebec.gouv.qc.ca/en/ShowDoc/cr/Q-2,%20r.%204.1 Accessed 2018-11-04].
[178] Government of Manitoba. 2011. Emissions Tax on Coal and Petroleum Coke [Online]. Available: https://www.gov.mb.ca/finance/taxation/taxes/coal.html Accessed 2018-11-06].
[179] Government of Alberta. 2007. Specified Gas Emitters Regulation [Online]. Available: http://aep.alberta.ca/climate-change/guidelines-legislation/specified-gas-emitters-regulation/documents/SpecifiedGasEmittersRegulation-139-2007.pdf Accessed [2018-11-04].
[180] Government of Quebec. 2018. The carbon market, a green economy growth tool [Online]. Available: http://webcache.googleusercontent.com/search?q=cache:http://www.mddelcc.gouv.qc.ca/changementsclimatiques/marche-carbone_en.asp Accessed 2018-04-11].
[181] Government of British Columbia. 2018. British Columbia's Carbon Tax [Online]. Available: https://www2.gov.bc.ca/gov/content/environment/climate-change/planning-and-action/carbon-tax Accessed 2018-11-04].
[182] Natural Resources Canada. 2016. Energy Efficiency Trends in Canada: 1990 to 2013 [Online]. Available: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/trends2013.pdf Accessed 12/01/2018 12/01/2018].
[183] CRH Canada. 2018. Climate change mitigation in cement industry [Online]. Available: https://www.crhcement.com/climate-change-mitigation/ Accessed 2018/11/04].
[184] National Energy Board. 2018. Industrial Energy Use in Canada - Emerging Trends - Energy Briefing Note [Online]. Available: https://www.neb-one.gc.ca/nrg/ntgrtd/mrkt/archive/2010ndstrlnrgscnd/ndstrlnrgscnd-eng.html Accessed 2018-11-04].
[185] Nimana B, Canter C, Kumar A. Energy consumption and greenhouse gas emissions in the recovery and extraction of crude bitumen from Canada's oil sands. Applied Energy. 2015;143:189-199.
[186] Oil Sands Magazine. 2018. Mining versus in-situ: a look at how energy companies are shifting their priorities [Online]. Available: http://www.oilsandsmagazine.com/news/2016/7/18/mining-versus-in-situ-how-energy-companies-are-shifting-their-priorities Accessed 02/04/2018].
[187] Natural Resources Canada. 2018. Directory of Energy Efficiency Programs for Industry [Online]. Available: http://oee.nrcan.gc.ca/industrial/financial-assistance/programs.cfm Accessed 2018-11-04].
[188] Energy and Mines Minsters's. 2015. Annex B: Industrial Energy Efficiency Programs Available Across Canada-Annex B [Online]. Available: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/www/pdf/publications/emmc/15-0140%20EMMC-Ind%20EE-Annex-B-e.pdf Accessed 2018/11/04].
[189] Natural Resources Canada. 2018. Financial assistance for energy management projects [Online]. Available: https://www.nrcan.gc.ca/energy/efficiency/industry/financial-assistance/20413#ISO Accessed 2018/11/04].

[190] Natural Resources Canada. 2018. ENERGY STAR Challenge for Industry [Online]. Available: https://www.nrcan.gc.ca/energy/efficiency/industry/cipec/20051 Accessed 2018/11/04].
[191] Energy and Mines Minsters'. 2015. Annex A: Industrial Energy Efficiency Collaboration Success Stories [Online]. Available: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/www/pdf/publications/emmc/15-0139%20EMMC-Ind%20EE-Annex-A-e.pdf Accessed 2018/11/04].
[192] Eriksson O, Finnveden G, Ekvall T, Björklund A. Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass-and natural gas combustion. Energy Policy. 2007;35:1346-1362.
[193] Cherubini F, Peters GP, Berntsen T, StrøMman AH, Hertwich E. CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. Gcb Bioenergy. 2011;3:413-426.
[194] Government of Ontario. 2018. The End of Coal [Online]. Available: https://www.ontario.ca/page/end-coal Accessed].
[195] International Institute for Sustainable Development. 2015. The End of Coal: Ontario's coal phase-out [Online]. Available: https://www.iisd.org/sites/default/files/publications/end-of-coal-ontario-coal-phase-out.pdf Accessed 2018-11-04].
[196] Statistics Canada. 2018. https://www150.statcan.gc.ca/n1/daily-quotidien/160310/t002b-eng.htm [Online]. Available: https://www150.statcan.gc.ca/n1/daily-quotidien/160310/t002b-eng.htm Accessed 2018/11/04].
[197] Cement Association of Canada. 2012. Environmental Performance Report - Concrete [Online]. Available: http://www.cement.ca/images/content/2012EnvironmentalPerformanceReport.pdf Accessed].
[198] Griffin B, Bennett M. 2017. Energy use and related data: Canadian cement manufacturing industry-1990 to 2015 [Online]. Available: http://www.sfu.ca/content/dam/sfu/ceedc/publications/cement/CIEEDAC%20-%20Cement%20Report%202017.pdf Accessed 20/04/2018].
[199] Nyboer J, Bennett M. 2013. Energy use and related data: Canadian iron and steel and ferro-alloy manufacturing industries 1990 to 2011 [Online]. Canadian Industrial Energy End-use Data and Analyis Center, Simon Fraser University, Burnaby, BC. Available: http://www3.cieedac.sfu.ca/CIEEDACweb/mod.php?mod=pub&op=user Accessed 24/08/2017].
[200] Government of Canada. 2018. Greenhouse gas emisisons from Canada's large-scale industrial plants [Online]. Available: http://indicators-map.canada.ca/App/Data?id=AirEmissions_GHG&GoCTemplateCulture=en-CA Accessed 2018/11/11].
[201] Government of Alberta Agriculture Food and Rural Development. 2018. Growing Forward 2 Program [Online]. Available: http://www.growingforward.alberta.ca/index.htm Accessed 23/04/2018].
[202] Government of British Columbia. 2019. Clean BC: Reducing pollution form industry [Online]. Available: https://cleanbc.gov.bc.ca/ Accessed 2019-02-15].
[203] Natural Resources Canada. 2018. Directory of energy efficiency and alternative energy programs in Canada [Online]. Available: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/policy_e/programs.cfm?searchtype=default&programtypes=all&regionaldeliveryid=all&sectoranditems=5%7C0&categoryid=all Accessed 11/04/2018].

[204] Natural Resource Canada. 2018. Energy and the economy [Online]. Available: https://www.nrcan.gc.ca/energy/facts/energy-economy/20062 Accessed 2018/11/18].
[205] Mission Innovation. 2018. Innovation Challenges [Online]. Available: http://mission-innovation.net/our-work/innovation-challenges/ Accessed 2018/11/18].
[206] Bataille C, Sawyer D, Melton N. 2015. Pathways to dep decarbonization in Canada [Online]. Available: http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_CAN.pdf Accessed 20/04/2018].
[207] Natural Resources Canada. 2018. Energy facts: energy and greenhouse gas emissions [Online]. Available: https://www.nrcan.gc.ca/energy/facts/energy-ghgs/20063 Accessed 20/04/2018].
[208] Leach A, Adams A, Cairns S, Coady L, Lambert G. 2015. Alberta Climate Leadership Plan, Report to Minister [Online]. Alberta, Canada: Government of Alberta. Available: https://www.alberta.ca/documents/climate/climate-leadership-report-to-minister.pdf Accessed 2019/02/13].
[209] Worrell E, Price L, Martin N, Hendriks C, Meida LO. Carbon dioxide emissions from the global cement industry 1. Annual Review of Energy and the Environment. 2001;26:303-329.
[210] Kajaste R, Hurme M. Cement industry greenhouse gas emissions – management options and abatement cost. Journal of Cleaner Production. 2016;112, Part 5:4041-4052.
[211] Organization for Economic Cooperation and Development. 2012. OECD Environmental Outlook to 2050: The consequences of inaction [Online]. Available: http://www.oecd-ilibrary.org/docserver/download/9712011e.pdf?expires=1491856596&id=id&accname=ocid177104&checksum=516FB2E94AAC036AE20703B00D38FA05 Accessed 2017].
[212] The European Cement Association. 2017. Key fact and statistics [Online]. Available: http://www.cembureau.be/about-cement/key-facts-figures Accessed].
[213] Benhelal E, Zahedi G, Shamsaei E, Bahadori A. Global strategies and potentials to curb CO2 emissions in cement industry. Journal of Cleaner Production. 2013;51:142-161.
[214] Liu F, Ross M, Wang S. Energy efficiency of China's cement industry. Energy. 1995;20:669-681.
[215] Pardo N, Moya JA, Mercier A. Prospective on the energy efficiency and CO2 emissions in the EU cement industry. Energy. 2011;36:3244-3254.
[216] Moya JA, Pardo N, Mercier A. The potential for improvements in energy efficiency and CO2 emissions in the EU27 cement industry and the relationship with the capital budgeting decision criteria. Journal of Cleaner Production. 2011;19:1207-1215.
[217] Worrell E, Martin N, Price L. Potentials for energy efficiency improvement in the US cement industry. Energy. 2000;25:1189-1214.
[218] Martin N, Worrell E, Price L. Energy efficiency and carbon dioxide emissions reduction opportunities in the US cement industry. Lawrence Berkeley National Laboratory. 1999.
[219] Madlool NA, Saidur R, Hossain MS, Rahim NA. A critical review on energy use and savings in the cement industries. Renewable and Sustainable Energy Reviews. 2011;15:2042-2060.
[220] Gielen D. CO2 removal in the iron and steel industry. Energy Conversion and Management. 2003;44:1027-1037.
[221] Worrell E. 2011. Energy Efficiency Improvement and Cost Saving Opportunities for the US Iron and Steel Industry An ENERGY STAR (R) Guide for Energy and Plant Managers [Online]. Available: https://www.energystar.gov/ia/business/industry/Iron_Steel_Guide.pdf Accessed 24/08/2017].

[222] Ren T, Patel MK. Basic petrochemicals from natural gas, coal and biomass: Energy use and CO2 emissions. Resources, Conservation and Recycling. 2009;53:513-528.
[223] International Energy Agency. 2013. Technology roadmap: energy and GHG reductions in the chamical industyr via catalytic processes [Online]. Available: http://www.iea.org/publications/freepublications/publication/technology-roadmap-chemical-industry-via-catalytic-processes.html Accessed].
[224] Ren T, Patel M, Blok K. Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes. Energy. 2006;31:425-451.
[225] Pillay P, Fendley KA. The contribution of energy efficient motors to demand and energy savings in the petrochemical industry. IEEE Transactions on Power Systems. 1995;10:1085-1093.
[226] Szklo AS, Soares JB, Tolmasquim McT. Economic potential of natural gas-fired cogeneration—analysis of Brazil's chemical industry. Energy Policy. 2004;32:1415-1428.
[227] Lin B, Wu Y, Zhang L. Estimates of the potential for energy conservation in the Chinese steel industry. Energy Policy. 2011;39:3680-3689.
[228] Gielen D, Moriguchi Y. CO2 in the iron and steel industry: an analysis of Japanese emission reduction potentials. Energy Policy. 2002;30:849-863.
[229] Neelis M, Patel M, Blok K, Haije W, Bach P. Approximation of theoretical energy-saving potentials for the petrochemical industry using energy balances for 68 key processes. Energy. 2007;32:1104-1123.
[230] Phylipsen D, Blok K, Worrell E, Beer Jd. Benchmarking the energy efficiency of Dutch industry: an assessment of the expected effect on energy consumption and CO2 emissions. Energy Policy. 2002;30:663-679.
[231] Saygin D, Patel MK, Worrell E, Tam C, Gielen DJ. Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector. Energy. 2011;36:5779-5790.
[232] McPherson M, Karney B. Long-term scenario alternatives and their implications: LEAP model application of Panama′ s electricity sector. Energy Policy. 2014;68:146-157.
[233] De Beer J. Potential for industrial energy-efficiency improvement in the long term. ed.: Kluwer Academic Publishers; 2000.
[234] Natural Resources Canada Office of Energy Efficiency. 2017. Comprehensive energy use database, 1990 to 2015 [Online]. Available: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_agg_ab.cfm Accessed 24/08/2017].
[235] Hasanbeigi A, Morrow W, Sathaye J, Masanet E, Xu T. A bottom-up model to estimate the energy efficiency improvement and CO 2 emission reduction potentials in the Chinese iron and steel industry. Energy. 2013;50:315-325.
[236] Wang K, Wang C, Lu X, Chen J. Scenario analysis on CO2 emissions reduction potential in China's iron and steel industry. Energy Policy. 2007;35:2320-2335.
[237] Cai W, Wang C, Wang K, Zhang Y, Chen J. Scenario analysis on CO2 emissions reduction potential in China's electricity sector. Energy Policy. 2007;35:6445-6456.
[238] Jun S, Lee S, Park J-W, Jeong S-J, Shin H-C. The assessment of renewable energy planning on CO2 abatement in South Korea. Renewable Energy. 2010;35:471-477.
[239] Huntzinger DN, Eatmon TD. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. Journal of Cleaner Production. 2009;17:668-675.

[240] Institute for Industrial Productivity. 2016. Industrial Efficiency Technolgy Database [Online]. Available: http://ietd.iipnetwork.org/ Accessed 06-29-2017].
[241] Worrell E, Galitsky C, Price L. Energy Efficiency Improvement Opportunities for the Cement Industry. 2008.
[242] Worrell E, Kermeli K, Galitsky C. 2013. Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making An ENERGY STAR® Guide for Energy and Plant Managers [Online]. EPA-United States Environmental Protection Agency. Available: https://www.energystar.gov/sites/default/files/buildings/tools/ENERGY%20STAR%20Guide%20for%20the%20Cement%20Industry%2028_08_2013%20Final.pdf Accessed 29/05/2017].
[243] Holderbank C. Present and future energy use of energy in the cement and concrete industries in Canada. CANMET Canada Cent Miner Energy Technol. 1993.
[244] Natural Ressources Canada. 2017. Comparehensive energy use database [Online]. Available: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=agg&juris=ca&rn=11&page=0 Accessed].
[245] Houghton J, Meira Filho L, Lim B, Treanton K, Mamaty I. Revised 1996 IPCC guidelines for national greenhouse gas inventories. v. 1: Greenhouse gas inventory reporting instructions.-v. 2: Greenhouse gas inventory workbook.-v. 3: Greenhouse gas inventory reference manual. 1997.
[246] Colin Sutherland DC. Northeastern North America Forecast 2014-2024 - Economic Growth, Construction & Cement Demand. 2013.
[247] Worrell E, Price L, Neelis M, Galitsky C, Zhou N. 2007. World best practice energy intensity values for selected industrial sectors [Online]. Available: https://eaei.lbl.gov/sites/all/files/industrial_best_practice_en.pdf Accessed 24/08/2017].
[248] Hasanbeigi A, Menke C, Therdyothin A. The use of conservation supply curves in energy policy and economic analysis: the case study of Thai cement industry. Energy Policy. 2010;38:392-405.
[249] Martin G, McGarel S, Evans T, Eklund G. Reduce Specific Energy Requirements while Optimizing NOx Emissions Decisions in Cement with Model Predictive Control. Personal Communication from Pavilion Technologies, Inc, Austin, TX. 2001.
[250] Price L, Hasanbeigi A, Lu H. 2009. Analysis of energy-efficiency opportunities for the cement industry in Shandong Province [Online]. Available: https://china.lbl.gov/sites/all/files/lbl-2751e-shandong-cementoct-2009.pdf Accessed].
[251] Cembureau-The European Cement Association. Best Available Techniques for the Cement Industry. A Contribution from the European Cement Industry to the Exchange of Information and Preparation of the IPPC BAT Reference Document for the Cement Industry on BAT Brussels. 1997.
[252] Dolores R, Moran M. Maintenance and production improvements with ASDs. In: editor.^editors. Proc 2001 IEEEIAS/PCA Cement Industry Technical Conference. ed.: 2001. p. 85-97.
[253] Fujimoto S. Modern technology impact on power usage in cement plants. Ieee Transactions on Industry Applications. 1994;30:553-560.
[254] Vleuten F. Cement in development energy and environment Netherlands. Energy Research Foundation. 1994.
[255] Venkateswaran S, Lowitt H. The US Cement Industry: an energy perspective. In: editor.^editors. ed.: Energetics, Inc., Columbia, MD (USA); 1988. p.

[256] European Cement Research Academy (ECRA) CSIC. 2009. Development of State of the Art - Techniques in Cement Manufacturing: Trying to Look Ahead" [Online]. Available: Accessed 06-29-2017].
[257] Goyenka PK, B.L. Saini, A. Gupta . . Energy Audit and Process Optimization: Vasavadatta Cement India. In: editor.^editors. 7Th NCB International Semianr on Cement and Building Materials. ed. New Dehli, India: 2000. p.
[258] Birch E. Energy Savings in Cement Kiln Systems. Energy Efficiency in the Cement Industry. 1990;12756:112.
[259] Regitz J. Evaluation of mill drive options. IEEE Transactions on Industry Applications. 1996;32:653-662.
[260] Simmons M, Gorby L, Terembula J. First vertical roller mill for cement grinding. In: editor.^editors. ed.: IEEE; 2005. p.
[261] Schneider U. From ordering to operation of the first QUADROPOL (R) roller mill at the Bosenberg cement works. ZKG INTERNATIONAL. 1999;52:460-+.
[262] Bhatty JI, Miller FM, Kosmatka SH, Bohan R. Innovations in Portland cement manufacturing. ed.: Portland Cement Association Skokie, Ill, USA; 2004.
[263] Parkes F. Energy saving by utilisation of high efficiency classifier for grinding and cooling of cement on two mills at castle cement (Ribblesdale) Limited, Clitheroe, Lancashire, UK. Energy Efficiency in the Cement Industry. 1990;12756:81.
[264] Benhelal E, Zahedi G, Hashim H. A novel design for green and economical cement manufacturing. Journal of Cleaner Production. 2012;22:60-66.
[265] Moya JA, Pardo N, Mercier A. The potential for improvements in energy efficiency and CO 2 emissions in the EU27 cement industry and the relationship with the capital budgeting decision criteria. Journal of Cleaner Production. 2011;19:1207-1215.
[266] Hasanbeigi A, Menke C, Price L. The CO 2 abatement cost curve for the Thailand cement industry. Journal of Cleaner Production. 2010;18:1509-1518.
[267] Ogbeide S. Developing an optimization model for CO2 reduction in cement production process. Journal of Engineering Science and Technology Review. 2010;3:85-88.
[268] Khurana S, Banerjee R, Gaitonde U. Energy balance and cogeneration for a cement plant. Applied Thermal Engineering. 2002;22:485-494.
[269] Kabir G, Abubakar A, El-Nafaty U. Energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant. Energy. 2010;35:1237-1243.
[270] Barker D, Turner S, Napier-Moore P, Clark M, Davison J. CO2 capture in the cement industry. Energy Procedia. 2009;1:87-94.
[271] Trade D. Sustainability Impact Assessment (SIA) Methodology: Towards an upgrade in 2004. In: editor.^editors. ed.: Draft; 2004. p.
[272] McIlveen-Wright D, Huang Y, Rezvani S, Wang Y. A technical and environmental analysis of co-combustion of coal and biomass in fluidised bed technologies. Fuel. 2007;86:2032-2042.
[273] Murray A, Horvath A, Nelson KL. Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: a case study from China. In: editor.^editors. ed.: ACS Publications; 2008. p.
[274] Damtoft J. Use of fly ash and other waste materials as raw feed and energy source in the Danish cement industry. In: editor.^editors. Proceedings of Three-Day CANMET/ACI International Symposium on Sustainable Development of Cement and Concrete Industry, Ottawa, Canada, CANMET/ACI. ed.: 1998. p. 95-105.

[275] Collins RJ, Ciesielski SK. Recycling and use of waste materials and by-products in highway construction. ed.: 1994.
[276] Martin G, McGarel S. Automation Using Model Predictive Control in the Cement Industry. Pavillion Technologies, Inc., Austin, TX (based on a paper published in International Cement Review, February 2001, pp. 66-67). In: editor.^editors. ed.: 2001. p.
[277] Hollingshead A, Venta G. Carbon Dioxide Reduction Technology Effectiveness Assessment–Initial Evaluation. Portland Cement Association (PCA), PCE R&D SN3125. 2009.
[278] Sirchis J. Energy efficiency in the cement industry. ed.: CRC Press; 1990.
[279] Natural Resources Canada. 2009. Canadian Cement Industry Energy Benchmarking [Online]. Available: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/Publications/industrial/cement-eng.pdf Accessed].
[280] Institute for Industrial Productivity. 2017. Industrial efficiency technology database [Online]. Available: http://ietd.iipnetwork.org/content/iron-and-steel Accessed 05/29/2017].
[281] Talaei A, Ahiduzzaman M, Kumar A. Long-term energy efficiency improvement and greenhouse gas emission mitigation in the chemical sector: A case study of Alberta, Canada.Manuscript submitted for publication. In: editor.^editors. ed.: 2017. p.
[282] National Energy Board. 2017. End-use prices: reference case - industrial sector [Online]. Available: https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2013/ppndcs/pxnds-eng.html Accessed [04/11/2017].
[283] World Steel Association. 2017. Steel statistical yearbook 2016 [Online]. Available: https://www.worldsteel.org/en/dam/jcr:37ad1117-fefc-4df3-b84f-6295478ae460/Steel+Statistical+Yearbook+2016.pdf Accessed 05/17/2017].
[284] World Steel Assossiation. 2010. Steel Statistical Yearbook 2010 [Online]. Available: https://www.worldsteel.org/en/dam/jcr:1ef195b3-1a46-41c2-b88b-6072c2687850/Steel+statistical+yearbook+2010.pdf Accessed 07/12/2017].
[285] West K. 2015. Energy technology perspective 2015: Iron and steel [Online]. Internaional Energy Agency, OECD steel comittee meeting. Available: https://www.oecd.org/sti/ind/Item%208b%20-%20IEA_ETP2015_OECD%20Steel%20Committee_final.pdf Accessed 05/17/2017].
[286] Carbon Capture Use and Storage Action Group. 2013. CCUS AG Working Group on CCS in Industrial Applications Background Paper [Online]. CCUS Action Groupon CCS in Indusrial Application-Preapared for IEA. Available: http://www.iea.org/media/workshops/2013/ccs/industry/backgroundpaper.pdf Accessed 07/12/2017].
[287] Arens M, Worrell E, Schleich J. Energy intensity development of the German iron and steel industry between 1991 and 2007. Energy. 2012;45:786-797.
[288] Columbia climate center. Mitigating iron and steel emissions [Online]. Available: http://climate.columbia.edu/files/2012/04/GNCS-Iron-Steel.pdf Accessed 05/17/2017].
[289] Bellevrat E, Menanteau P. Introducing carbon constraint in the steel sector: ULCOS scenarios and economic modeling. Revue de Métallurgie. 2009;106:318-324.
[290] Worrell E, Laitner JA, Ruth M, Finman H. Productivity benefits of industrial energy efficiency measures. Energy. 2003;28:1081-1098.
[291] World Steel Assossiation. 2017. Sustainability indicators for iron and steel industry [Online]. Available: https://www.worldsteel.org/steel-by-topic/sustainability/sustainability-indicators0.html Accessed 05/17/2017].

[292] Worrell E, Price L, Neelis M, Galitsky C, Zhou N. World best practice energy intensity values for selected industrial sectors. Lawrence Berkeley National Laboratory. 2007.
[293] Hasanbeigi A, Arens M, Price L. Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review. Renewable and Sustainable Energy Reviews. 2014;33:645-658.
[294] Energetics. 2005. Steel Industry Marginal Opportunity Study [Online]. Available: http://energy.gov/sites/prod/files/2013/11/f4/steelmarginalopportunity.pdf Accessed 07/14/2017].
[295] Wen Z, Meng F, Chen M. Estimates of the potential for energy conservation and CO2 emissions mitigation based on Asian-Pacific Integrated Model (AIM): the case of the iron and steel industry in China. Journal of Cleaner Production. 2014;65:120-130.
[296] Orth A, Anastasijevic N, Eichberger H. Low CO2 emission technologies for iron and steelmaking as well as titania slag production. Minerals Engineering. 2007;20:854-861.
[297] Xu C, Cang D-q. A Brief Overview of Low CO2 Emission Technologies for Iron and Steel Making. Journal of Iron and Steel Research, International. 2010;17:1-7.
[298] Morrow WR, Hasanbeigi A, Sathaye J, Xu T. Assessment of energy efficiency improvement and CO 2 emission reduction potentials in India's cement and iron & steel industries. Journal of Cleaner Production. 2014;65:131-141.
[299] Worrell E, Price L, Martin N. Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. Energy. 2001;26:513-536.
[300] Government of Canada. 2014. Canada's sixth national report on climate change [Online]. Ministry of Environment, Government of Canada. Available: https://ec.gc.ca/cc/16153A64-BDA4-4DBB-A514-B159C5149B55/6458_EC_ID1180-MainBook_high_min%20FINAL-s.pdf Accessed 07/17/2017].
[301] Davis M, Ahiduzzaman M, Kumar A. How to model a complex national energy system? Developing an integrated energy systems framework for long-term energy and emissions analysis. International Journal of Global Warming. 2019;17:23-58.
[302] Davis M. The Development of a Technology-Explicit Bottom-Up Integrated Multi-Regional Energy Model of Canada. University of Alberta; 2017.
[303] Bonyad M, Shafique HU, Mondal MAH, Subramanyam V, Kumar A, Ahiduzzaman M. The development of a framework for the assessment of energy demand-based greenhouse gas mitigation options for the agriculture sector. 2018.
[304] Talaei A, Pier D, Iyer A, Ahiduzzaman M, Kumar A. Development of long-term energy efficiency improvement and greenhouse gas emissions mitigation options for the cement industry. In: editor.^editors. ed.: 2018. p.
[305] World Steel Association. 2013. World Steel in Figures 2013 [Online]. World Steel Association. Available: https://www.worldsteel.org/en/dam/jcr:7bb9ac20-009d-4c42-96b6-87e2904a721c/Steel-Statistical-Yearbook-2013.pdf Accessed 24/08/2017].
[306] Canadian Steel Producers Association. 2014. Steel Facts [Online]. Canadian Steel Producers Association. Available: http://canadiansteel.ca/steel-facts/ Accessed 6/4/2014].
[307] Hidalgo I, Szabo L, Calleja I, Císcar JC, Russ P, Soria A. Energy consumption and CO_2 emissions from the world iron and steel industry. JRC-IPTS EUR. 2003;20686.
[308] Jamison K, Kramer C, Brueske S, Fisher A. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in US Iron and Steel Manufacturing. In: editor.^editors. ed.: Energetics; 2015. p.

[309] Gielen D, Moriguchi Y. 2001. Environmental Strategy design for the Japanese Iron and Steel Industry, A Global Perspective [Online]. Available: https://www.gtap.agecon.purdue.edu/resources/download/461.pdf Accessed 07/17/2017].
[310] Warrian P. 2010. The importance of steel manufactoring to Canada-a research study [Online]. Munk Centre, University of Toronto. Available: http://munkschool.utoronto.ca/wp-content/uploads/2013/05/CSPA_report_web.pdf Accessed 07/21/2017].
[311] Energetics. 2000. Energy and environmental profile of the U.S. Iron and Steel Indusry [Online]. Energetic, Incorporated prepared for U.S. Department of Energy, Office of Industrial Technologies. Available: https://energy.gov/sites/prod/files/2013/11/f4/steel_profile.pdf Accessed 07/17/2017].
[312] Energetics. 2004. Steel Industry Energy Bandwidth Study [Online]. Energetics Inc for U.S. Department of Enerty Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program. Available: https://energy.gov/sites/prod/files/2013/11/f4/steelbandwidthstudy.pdf Accessed 24/08/2017].
[313] Sakamoto Y, Tonooka Y, Yanagisawa Y. Estimation of energy consumption for each process in the Japanese steel industry: a process analysis. Energy Conversion and Management. 1999;40:1129-1140.
[314] World Steel Association. 2016. Energy use in the steel industry [Online]. World Steel Association. Available: https://www.worldsteel.org/en/dam/jcr:f07b864c-908e-4229-9f92-669f1c3abf4c/fact_energy_2016.pdf Accessed 07/01/2017].
[315] Hasanbeigi A, Price L, Aden N, Chunxia Z, Xiuping L, Fangqin S. 2011. A Comparison of Iron and Steel Production Energy Use and Energy Intensity in China and the U.S. [Online]. Ernest Orlando Lawrence Berkeley National Laboratory. Available: http://china.lbl.gov/sites/all/files/lbl-4836e-us-china-steeljune-2011.pdf Accessed 24/08/2017].
[316] American Iron and Steel Institute 2005. Saving One Barrell of Oil per Ton (SOBOT) A New Roadmap for Transformation of Steelmaking Process [Online]. American Iron and Steel Institute Available: https://www.steel.org/~/media/Files/AISI/Public%20Policy/saving_one_barrel_oil_per_ton.pdf Accessed 24/08/2017].
[317] Remus R, Monsonet MAA, Roudier S, Sancho LD. 2013. Best available techniques (BAT) reference document for iron and steel production [Online]. Seville, Spain: European Commission Joint Research Center (JRC). Available: http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf Accessed 24/08/2017].
[318] Hasanbeigi A, Price L. 2013. Emerging Energy-efficiency and Carbon Dioxide Emissions-reduction Technologies for the Iron and Steel Industry [Online]. Available: http://china.lbl.gov/sites/all/files/6106e-steel-tech.pdf Accessed 24/08/2017].
[319] Li Y, Zhu L. Cost of energy saving and CO_2 emissions reduction in China’s iron and steel sector. Applied Energy. 2014:603-616.
[320] Birat J-P, Lorrain J-P, de Lassat Y. The “CO2 Tool”: CO2 emissions & energy consumption of existing & breakthrough steelmaking routes. Revue de Métallurgie. 2009;106:325-336.
[321] Porzio GF, Fornai B, Amato A, Matarese N, Vannucci M, Chiappelli L, Colla V. Reducing the energy consumption and CO2 emissions of energy intensive industries through decision support systems – An example of application to the steel industry. Applied Energy. 2013;112:818-833.
[322] Worrell E. personal coversation. In: editor.^editors. ed.: 2014. p.

[323] Kirschen M, Risonarta V, Pfeifer H. Energy efficiency and the influence of gas burners to the energy related carbon dioxide emissions of electric arc furnaces in steel industry. Energy. 2009;34:1065-1072.
[324] Hasanbeigi A, Price L, McKane A. The State–of-the-Art Clean Technologies (SOACT) for Steelmaking Handbook. In: editor.^editors. 2nd Edition. ed.: Asia-Pacific Partnership on Clean Development and Climate; 2010. p.
[325] Worrell E, Blinde P, Neelis M, Blomen E, Masanet E. Energy efficiency improvement and cost saving opportunities for the US iron and steel industry an ENERGY STAR (R) guide for energy and plant managers. 2011.
[326] United States Environmental Protetection Agency. 2018. Global greenhouse gas emissions data [Online]. Available: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data Accessed [13/03/2018].
[327] Mazziotti Gomez de Teran C, Fiore D, Favaroni M, Fardelli A. Overview of technologies for improving energy efficiency from energy intensive industries derived from the Italian national experience in IPPC permit licensing. Journal of Cleaner Production. 2017;168:1547-1558.
[328] Yáñez E, Ramírez A, Uribe A, Castillo E, Faaij A. Unravelling the potential of energy efficiency in the Colombian oil industry. Journal of Cleaner Production. 2018;176:604-628.
[329] Worrell E, Corsten M, Galitsky C. 2015. Energy eEfficiency improvement and cost saving opportunities for petroleum refineries: An ENERGY STAR® guide for energy and plant managers [Online]. Available: https://www.energystar.gov/sites/default/files/tools/ENERGY_STAR_Guide_Petroleum_Refineries_20150330.pdf Accessed 16/02/2017].
[330] Hasheminasab H, Gholipour Y, Kharrazi M, Streimikiene D. A novel metric of sustainability for petroleum refinery projects. Journal of Cleaner Production. 2018;171:1215-1224.
[331] Weng Y, Yan G, Li Y, Guo S. Integrated substance and energy flow analysis towards CO_2 emission evaluation of gasoline & diesel production in Chinese fuel-refinery. Journal of Cleaner Production. 2016;112:4107-4113.
[332] Hadidi LA, AlDosary AS, Al-Matar AK, Mudallah OA. An optimization model to improve gas emission mitigation in oil refineries. Journal of Cleaner Production. 2016;118:29-36.
[333] Bulasara VK, Uppaluri R, Ghoshal AK. Revamp study of crude distillation unit heat exchanger network: Energy integration potential of delayed coking unit free hot streams. Applied thermal engineering. 2009;29:2271-2279.
[334] Liu XG, He C, He CC, Chen JJ, Zhang BJ, Chen QL. A new retrofit approach to the absorption-stabilization process for improving energy efficiency in refineries. Energy. 2017;118:1131-1145.
[335] Holmgren K, Sternhufvud C. CO_2-emission reduction costs for petroleum refineries in Sweden. Journal of Cleaner Production. 2008;16:385-394.
[336] Environmental Protection Agency. 2010. Available and emerging technologies for reducing greenhouse gas emissions from the petroleum refining industry [Online]. Available: https://www.epa.gov/sites/production/files/2015-12/documents/refineries.pdf Accessed 18/10/2017].
[337] Worrell E, Galitsky C. 2005. Energy efficiency improvement and cost saving opportunities for petroleum refineries [Online]. Available: https://escholarship.org/uc/item/96m8d8gm Accessed 2019/02/13].

[338] Oyedun AO, Kumar A, Oestreich D, Arnold U, Sauer J. The development of the production cost of oxymethylene ethers as diesel additives from biomass. Biofuels, Bioproducts and Biorefining. 2018;12:694-710.
[339] Luyben WL. Process Modeling,Simulation and Control for Chemical Engineers. ed.: McGraw-Hill Higher Education; 1989.
[340] Hall SM. Chapter 19 - Energy Conservation. In: Hall SM, editor.^editors. Rules of Thumb for Chemical Engineers (Sixth Edition). ed.: Elsevier; 2018. p. 345-354.
[341] AlNouss A, Ibrahim M, Al-Sobhi SA. Potential energy savings and greenhouse gases (GHGs) emissions reduction strategy for natural gas liquid (NGL) recovery: Process simulation and economic evaluation. Journal of Cleaner Production. 2018;194:525-539.
[342] Behroozsarand A, Zamaniyan A. Simulation and optimization of an integrated GTL process. Journal of Cleaner Production. 2017;142:2315-2327.
[343] International Energy Agency. 2016. Kew world energy statistics [Online]. Available: https://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf Accessed 11/10/2017].
[344] Hydrocarbons technology. 2013. The 10 biggest oil refining countries [Online]. Available: http://www.hydrocarbons-technology.com/features/featurethe-10-biggest-oil-refining-countries/ Accessed 18/10/2017].
[345] Canadian Fuel Association. 2015. How Canadian refineries are reducing GHG emissions [Online]. Available: http://www.canadianfuels.ca/Blog/May-2015/How-Canadian-refineries-are-reducing-GHG-emissions/ Accessed 11/10/2017].
[346] Natural Resources Canada. 2017. Energy fact book 2016-17 [Online]. Available: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/EnergyFactBook_2016_17_En.pdf Accessed 18/10/2017].
[347] Alberta Goverement. 2017. Alberta major projects: An inventory of private and public sector projects in Alberta valued at $5 million or greater. [Online]. Available: http://majorprojects.alberta.ca/ Accessed 2019/02/13].
[348] Worrell E, Corsten M, Galitsky C. Energy efficiency improvement and cost saving opportunities for petroleum refineries: An ENERGY STAR ® Guide for Energy and Plant Managers Lawrence Berkeley National Laboratory. 2015.
[349] Fusfeld H. 1983. Industrial energy use [Online]. Available: https://www.princeton.edu/~ota/disk3/1983/8312/831208.PDF Accessed 10/10/2016].
[350] Wang M, Lee H, Molburg J. Allocation of energy use in petroleum refineries to petroleum products. The International Journal of Life Cycle Assessment. 2004;9:34-44.
[351] Chan WN, Walter A, Sugiyama MI, Borges GC. Assessment of CO_2 emission mitigation for a Brazilian oil refinery. Brazilian Journal of Chemical Engineering. 2016;33:835-850.
[352] Han J, Forman GS, Elgowainy A, Cai H, Wang M, DiVita VB. A comparative assessment of resource efficiency in petroleum refining. Fuel. 2015;157:292-298.
[353] Elgowainy A, Han J, Cai H, Wang M, Forman GS, DiVita VB. Energy efficiency and greenhouse gas emission intensity of petroleum products at U.S. refineries. Environmental science & technology. 2014;48:7612-7624.
[354] Abella JP, Bergerson JA. Model to investigate energy and greenhouse gas emissions implications of refining petroleum: impacts of crude quality and refinery configuration. Environmental science & technology. 2012;46:13037-13047.
[355] Natural Resources Canada Office of Energy Efficiency. 2016. Secondary energy use and GHG emissions by industry [Online]. Available:

http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=agg&juris=ab&rn=2&page=0 Accessed 16/10/2016].
[356] Canadian Association of Petroleum Producers. 2016. CAPP's statistical handbook is a historical summary of the petroleum industry's progress [Online]. Available: http://www.capp.ca/publications-and-statistics/statistics/statistical-handbook Accessed 19/07/2017].
[357] Stockholm Environment Institute. 2016. An introduction to the Long-range Energy Alternative Planning System [Online]. Stockholdm Environment Institute. Available: https://www.energycommunity.org/default.asp?action=introduction Accessed 10/11/2016].
[358] US Environmental Protection Agency. 2014. Emission factors for greenhouse gas inventories [Online]. US Environmental Protection Agency. Available: https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf Accessed 10/26/2016].
[359] Canadian Association of Petroleum Producers. 2017. Statistical handbook: refinery and upgrader capacity [Online]. Available: http://www.capp.ca/publications-and-statistics/statistics/statistical-handbook Accessed 11/02/2017].
[360] Alberta Energy Regulator. 2017. Plants and facilities [Online]. Available: http://www.aer.ca/data-and-publications/statistical-reports/plants-and-facilities Accessed 11/04/2017].
[361] Bickis I. Alberta refinery costs level at $8.5 billion, on track for start date. In: editor.^editors. Global news. ed.: 2015. p.
[362] Alberta Goverement. 2017. North west bitumen refinery-Phase 1 [Online]. Available: http://majorprojects.alberta.ca/details/North-West-Bitumen-Refinery-Phase-1/550 Accessed 02/08/2017].
[363] Sturgeon Refinery. 2017. Project update: May 2017 [Online]. Available: https://nwrsturgeonrefinery.com/news/project-update-may-2017/ Accessed 02/08/2017].
[364] Government of Alberta. 2018. Carbon Competitivenss Incentive Regulation [Online]. Available: https://www.alberta.ca/carbon-competitiveness-incentive-regulation.aspx Accessed 2018/11/11].
[365] Government of Alberta. 2018. Regulated facilities-fact sheet [Online]. Available: https://www.alberta.ca/assets/documents/cci-regulated-facility-fact-sheet.pdf Accessed 2018/11/11].
[366] Alberta Energy. 2014. Upgrading and refining [Online]. Alberta Government. Available: http://www.energy.alberta.ca/Oil/pdfs/FSRefiningUpgrading.pdf Accessed 25/11/2016].
[367] Alberta Energy Regulator. 2017. Plants and facilities [Online]. Available: http://www.aer.ca/data-and-publications/statistical-reports/plants-and-facilities Accessed 07/21/2017].
[368] Government of Alberta. 2018. Standard for Establishing and Assigning Benchmarks V2.1 [Online]. Available: https://www.alberta.ca/assets/documents/cci-standard-establishing-assigning-benchmarks.pdf Accessed 2018/11/11].
[369] Government of Alberta. 2017. Climate change and emissions managment act-Carbon Competitiveness Incentive Regulation [Online]. Available: http://www.qp.alberta.ca/documents/Regs/2017_255.pdf Accessed 2018/11/12].
[370] Petrick M, Pellegrino J. The potential for reducing energy utilization in the refining industry. In: editor.^editors. ed.: Argonne National Lab., IL (US); 1999. p.

[371] Nordrum S, Lieberman D, Colombo M, Gorski A, Webb C. Assessment of greenhouse gas mitigation options and costs for California Petroleum Industry facilities: The shape of things to come. Energy Procedia. 2011;4:5729-5737.
[372] van Straelen J, Geuzebroek F, Goodchild N, Protopapas G, Mahony L. CO2 capture for refineries, a practical approach. International Journal of Greenhouse Gas Control. 2010;4:316-320.
[373] Wang J, O'Donnell J, Brandt AR. Potential solar energy use in the global petroleum sector. Energy. 2017;118:884-892.
[374] de Lima RS, Schaeffer R. The energy efficiency of crude oil refining in Brazil: A Brazilian refinery plant case. Energy. 2011;36:3101-3112.
[375] International Energy Agency Greenhouse Gas R&D Programme. 1999. The reduction of greenhouse gas emission from the oil refining and petrochemical industry [Online]. Available: http://ieaghg.org/docs/General_Docs/Reports/PH3%20-%208%20-%20Oil%20refining%20and%20petrochemicals.pdf Accessed 10/10/2017].
[376] Statistics Canada. 2018. Average inflation in the All-items Consumer Price Index (CPI) and aggregates, Canada, provinces and territories [Online]. Available: https://www150.statcan.gc.ca/n1/pub/11-626-x/2013025/tbl/tbl01-eng.htm Accessed [2019/01/25].
[377] Mclnerney T, McPherson M. 2018. Alberta Replaces Specified Gas Emitters Regulation with Carbon Competitiveness Incentive Regulation [Online]. Available: https://www.bennettjones.com/en/Blogs-Section/Alberta-Replaces-Specified-Gas-Emitters-Regulation-with-Carbon-Competitiveness-Incentive-Regulation Accessed 2018/11/11].
[378] International Energy Agency. 2016. Energy balance statistics [Online]. Available: http://www.iea.org/statistics/topics/energybalances/ Accessed].
[379] Menezes FM, Goes MF, Kalid RA, Tanimoto AH, Andrade JC. Economic feasibility of an energy efficiency project for a steam distribution system in a chemical industry. Independent Jouranal of Managment and Production. 2017;8:1381-1399.
[380] Fan T, Luo R, Xia H, Li X. Using LMDI method to analyze the influencing factors of carbon emissions in China's petrochemical industries. Natural Hazards. 2015;75:319-332.
[381] Griffin PW, Hammond GP, Norman JB. Opportunities for Energy Demand and Carbon Emissions Reduction in the Chemicals Sector. Energy Procedia. 2017;105:4347-4356.
[382] Chan DY-L, Huang C-F, Lin W-C, Hong G-B. Energy efficiency benchmarking of energy-intensive industries in Taiwan. Energy Conversion and Management. 2014;77:216-220.
[383] Levi PG, Cullen JM. Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products. Environmental science & technology. 2018;52:1725-1734.
[384] Ren T. Barriers and drivers for process innovation in the petrochemical industry: A case study. Journal of Engineering and Technology Management. 2009;26:285-304.
[385] Zhou W, Zhu B, Li Q, Ma T, Hu S, Griffy-Brown C. CO2 emissions and mitigation potential in China's ammonia industry. Energy Policy. 2010;38:3701-3709.
[386] Griffin PW, Hammond GP, Norman JB. Industrial energy use and carbon emissions reduction in the chemicals sector: A UK perspective. Applied Energy. 2017.
[387] Tantisattayakul T, Soontharothai J, Limphitakphong N, Pharino C, Chavalparit O, Kanchanapiya P. Assessment of energy efficiency measures in the petrochemical industry in Thailand. Journal of Cleaner Production. 2016;137:931-941.
[388] Worrell E, Blok K. Energy savings in the nitrogen fertilizer industry in the Netherlands. Energy. 1994;19:195-209.

[389] Taibi E, Gielen D, Bazilian M. The potential for renewable energy in industrial applications. Renewable and Sustainable Energy Reviews. 2012;16:735-744.
[390] Zhou W, Zhu B, Li Q, Ma T, Hu S, Griffy-Brown C. CO 2 emissions and mitigation potential in China's ammonia industry. Energy Policy. 2010;38:3701-3709.
[391] Lin B, Zhang L, Wu Y. Evaluation of electricity saving potential in China's chemical industry based on cointegration. Energy Policy. 2012;44:320-330.
[392] Worrell E, Phylipsen D, Einstein D, Martin N. 2000. Energy use and energy intensity of the US chemical industry [Online]. Available: https://pdfs.semanticscholar.org/099c/8d74f420b421d9188329c9f0f1e1f01acc55.pdf Accessed].
[393] HEAPS CG. 2017. Long-range Energy Alternatives Planning (LEAP) system. [Software version: 2015.0.19.0] [Online]. Stockholm Environment Institute. Somerville, MA, USA. Available: https://www.energycommunity.org Accessed 12/09/2017].
[394] Alberta Energy. 2008. Petrochemicals [Online]. Alberta Department of Energy. Available: http://www.energy.alberta.ca/EnergyProcessing/pdfs/Petrochemicals_brochure_overview.pdf Accessed].
[395] Central Alberta Economic Partnership. 2009. Chemical and Petrochemicals: a $9.5 Billion Industry in Alberta [Online]. Red Dear Alberta: Central Alberta Economic Partnership Ltd. . Available: http://centralalberta.ab.ca/assets/documents/sectorPro_petro.pdf Accessed].
[396] Western Economic Diversification Canada. 2015. Clobal compatitiveness snapshot: industrial chemicals [Online]. Western Economic Diversification Canada. Available: http://www.wd-deo.gc.ca/eng/home.asp Accessed 5/12/15].
[397] Cheminfo Services Inc. 2014. Bio based cheimal import replacement initiative: chemical markets and biochemical options for Alberta [Online]. Prepared for Enterprise and Advanced Eduction, Government of Alberta. Available: https://www.albertacanada.com/files/albertacanada/BioBased-Chemical-Import-Replacement-Report_Full-Report(237_pages).pdf Accessed].
[398] International Energy Agency. 2007. Tracking Industrial Energy Efficiency and CO_2 Emissions, Paris, France: International Energy Agency, [Online]. Available: https://www.iea.org/publications/freepublications/publication/tracking_emissions.pdf Accessed 24/08/2017].
[399] Ren T, Patel MK, Blok K. Steam cracking and methane to olefins: energy use, CO 2 emissions and production costs. Energy. 2008;33:817-833.
[400] Brookes G. Energy consumption and conservation in thefertilizer industry. In: editor.^editors. Energy Audit Series; No13: The fertilizer industry. ed.: Department of Energy and Department of Industry; 1981. p.
[401] Natural Resources Canada. 2008. Canadian Ammonia Producers: Benchmarking energy efficiency and carbon dioxide emissions [Online]. Ottawa, Canada. Available: http://www.nrcan.gc.ca/sites/oee.nrcan.gc.ca/files/files/pdf/industrial/ammonia-study.pdf Accessed].
[402] Rafiqul I, Weber C, Lehmann B, Voss A. Energy efficiency improvements in ammonia production—perspectives and uncertainties. Energy. 2005;30:2487-2504.
[403] IFFCO. 2013. Fertilizer pruduction plant projet: environmental impact assessment [Online]. IFFCO Canada submitted to the Ministry of sustainable development, environment, wildelife and parks. Available: http://iffcocan.com/iffco/seia-main-report-id-659.pdf Accessed].
[404] Kumar A, Subramanyam V, Kabir MR. 2011. Development of energy, emission and water flow sankey diagrams for the Province of Alberta through modelling. Final Report. [Online].

Available: http://eipa.alberta.ca/media/43317/sankey-diagram-energy-emission-water-flows.pdf Accessed].
[405] Subramanyam V, Kumar A. 2012. Development of best economic options for GHG mitigation in Alberta. Final Report, March 2012. [Online]. Available: https://www.researchgate.net/publication/234481304_Development_of_Greenhouse_Gas_Mitigation_Options_for_Alberta's_Energy_Sector Accessed].
[406] Subramanyam V, Kumar A. Identification of best energy efficiency opportunities in Alberta's energy sector – Phase I. Final Report submitted to the Alberta Innovates – Energy and Environment Solutions (EES), 1800 Phipps Mckinnon Building, 10020 101A Avenue, T5J 3G2 Edmonton, Alberta. In: editor.^editors. ed.: 2012. p.
[407] Subramanyam V, Paramshivan D, Kumar A, Mondal A. Using sankey diagrams to map energy flow from primary fuel to end use. Energy Conversion and Management. 2015;91:342–352.
[408] Subramanyam V, Paramashivan D, Radpour S, Shah T, Kumar A. 2013. Identification of best energy-efficiency opportunities in Alberta's energy sector- Phase II. GHG mitigation cost curves for the residential, commercial and transport sectors of Alberta. Final report, November 2013. [Online]. Available: Accessed].
[409] Nyboer J, Griffin B. Energy use and related data: Canadian chemistry industry 1990-2014. In: editor.^editors. ed.: Canadian industrial energy end-use data and analysis center, Simon Fraser University, Burnaby, BC; 2016. p.
[410] Natural Resources Canada. Industrial Consumption of Energy (ICE) Survey Summary Report of Energy Use in the Canadian Manufacturing Sector 19 9 5 –2 011. In: editor.^editors. ed.: Energy Publications, Office of Energy Efficiency, Natural Resources Canada,c/o St. Joseph Communications, Order Processing Unit, 1165 Kenaston Street, Ottawa ON K1G 6S; 2011. p.
[411] Canadian Energy Research Institute. 2015. Examining the expansion potential of the petrochemical industry in Canada [Online]. Available: http://static1.squarespace.com/static/557705f1e4b0c73f726133e1/t/569549a21c12108457550567/1452624294192/CERI+Study+153+-+final+report.pdf Accessed].
[412] Government of Alberta. 2013. Alberta Environment and Sustainable Resource Development: Report on 2011 Greenhouse Gas Emissions [Online]. Climate Change Secretariat Environmental Policy Division Alberta Environment and Sustainable Resource Development, 12th floor, Baker Centre, 10025 106th Street, Edmonton, AB, T5J 1G4 Available: http://open.alberta.ca/dataset/7106a70d-2f97-41f7-8b5a-8f734209eaae/resource/fe6a89a9-536e-4340-9438-23ee47683cbd/download/2013-05-2011ReportGreenhouseGasEmissions.pdf Accessed].
[413] American Chemistry Council. 2013. Shale gas, competitiveness, and new US chemical industry investment: An analysis based on annoced projects [Online]. Available: https://chemistrytoenergy.com/sites/chemistrytoenergy.com/files/shale-gas-full-study.pdf Accessed].
[414] Morgan G. Canadian Market primed for petrochemcial production boost. In: editor.^editors. Financial Post. ed.: 2015. p.
[415] Murillo C. 2014. Shale gas and petrochemical feedstock in Alberta: Understanding fracking, environmental impacts and feedstock availability [Online]. Available: https://www.albertacanada.com/taiwan/documents/CarlosMurilloPresentation.pdf Accessed 04/16/2014].

[416] Chemistry Industry Assossiation of Canada. 2015. 2014 year-end survey of business conditions [Online]. Available: http://www.canadianchemistry.ca/library/uploads/year_end_report_2014.pdf Accessed].
[417] Omran S. Alberta launches $500M incentive program for petrochemical sector growth. In: editor.^editors. Canada Business review. ed.: 2016. p.
[418] Ammonia Industry. 2016. Ammonia plants in North America [Online]. Available: https://www.google.com/fusiontables/data?docid=1vXUF9q5X0vbWID_JAzpxaByp28lwlr3gs0y2zg8#rows:id=1 Accessed].
[419] Ma D, Hasanbeigi A, Price L, Chen W. Assessment of energy-saving and emission reduction potentials in China's ammonia industry. Clean Technologies and Environmental Policy. 2015:1-12.
[420] Johansson TB, Nakićenović N. 2012. Global energy assessment: toward a sustainable future [Online]. Cambridge University Press. Available: http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA-Summary-web.pdf Accessed 24/08/2017].
[421] Nand S, Goswami M. Safety and Reliability in Operation of Indian Ammonia and Urea Plants. 54 th AIChE Annual Safety in Ammonia Plants and Related Facilities. 2009:13-17.
[422] Worrell E, Bernstein L, Roy J, Price L, Harnisch J. Industrial energy efficiency and climate change mitigation. Energy efficiency. 2009;2:109-123.
[423] FUTURE TECHNOLOGIES FOR ENERGY-EFFICIENT IRON AND STEEL MAKING. Annual Review of Energy and the Environment. 1998;23:123-205.
[424] Bojdys M. Assessment of Energy Savings. Benefits of Mechanical Preheater and Blending Silo Feeding with Bucket Elevators. AUMUND Fördertechnik Germany. 2002.
[425] Chatterjee A. Materials preparation and raw milling. Innovations in portland cement manufacturing, Portland Cement Association, Skokie, IL. 2004.
[426] Süssegger A, KHD Humboldt Wedag, Cologne, Germany. Modern Roller Press Technology. Separator-Report '92" Proc KHD Symposium '92, . 1993;Volume 1
[427] Philips K, Enviro-Seal P. Case Study—M/S Maihar cement. In: editor.^editors. ed.: 2001. p.
[428] Börrnert T, Bürki T. Waste heat conversion into electricity. In: editor.^editors. Cement Industry Technical Conference, 2010 IEEE-IAS/PCA 52nd. ed.: IEEE; 2010. p. 1-8.
[429] Bolwerk R, Ebertsch G, Heinrich M, Plickert S, Oerter M. German Contribution to the Review of the Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries–Part II: Cement Manufacturing Industries. Germany, June. 2006.
[430] Sauli R. Rotary kiln modernization and clinker production increase at testi cement plant of SACCI Spa. In: editor.^editors. Italy Proc KHD Symposium. ed.: 1993. p.
[431] Ooi TC, Thompson D, Anderson DR, Fisher R, Fray T, Zandi M. The effect of charcoal combustion on iron-ore sintering performance and emission of persistent organic pollutants. Combustion and Flame. 2011;158:979-987.
[432] Warell L, Olsson A. 2009. Trends and developments in the intensity of steel use: an econometric analysis [Online]. Available: https://www.diva-portal.org/smash/get/diva2:1001923/FULLTEXT01.pdf Accessed 24/08/2017].
[433] International Energy Agency. 2013. Tracking Clean Energy Progress 2013: IEA Input to the Clean Energy Ministerial [Online]. International Energy Agency. Available: http://www.iea.org/publications/tcep_web.pdf Accessed 24/08/2017].

[434] Johansson TB, Patwardhan AP, Nakićenović N, Gomez-Echeverri L. Global Energy Assessment: Toward a Sustainable Future. ed.: Cambridge University Press; 2012.
[435] Organisation for Economic Co-operation and Development. 2011. Making steel more green: challenges and opportunities [Online]. Paris. Available: http://www.oecd.org/sti/ind/48328101.pdf Accessed 24/08/2017].
[436] Statistics Canada. 2010. Population Projections for Canada, Provinces and Territories (2009-2036) [Online]. Ottawa: Statistics Canada, Demography Division Available: http://www.statcan.gc.ca/pub/91-520-x/91-520-x2010001-eng.pdf Accessed 07/02/2017].
[437] International Energy Agency. 2009. Chemical and Petrochemical Sector: Potential of best practice technology and other measures for improving energy efficiency. International Energy Agency, OECD/IEA, Paris. [Online]. Available: https://www.iea.org/publications/freepublications/publication/chemical_petrochemical_sector.pdf Accessed].
[438] Government of Alberta. 2012. Alberta's Energy Industry: An Overview. June 2012. Alberta Government [Online]. Available: http://www.energy.alberta.ca/org/pdfs/Alberta_Energy_Overview.pdf Accessed].
[439] Stephen JD, Mabee VE, MacLean HL. Material Switching in Alberta: Opportunity and gap analysis for advancing meaningful biological greenhouse gas reductions. Submitted to Alberta Innovates - Bio Solutions. In: editor.^editors. ed.: 2012. p.
[440] Alberta Environment. 1999. Wastewater management review for the fertilizer manufacturin sector [Online]. Edmonton, Alberta: Alberta Environment, Environmental Science Devision, Environmental Service. Available: https://archive.org/details/wastewatermanage00albe.