SASKATCHEWAN ELECTRICAL POWER SYSTEMS PLANNING UNDER STOCHASTIC CONDITIONS AND FEDERAL CLIMATE CHANGE REGULATIONS

A Thesis

Submitted to the Faculty of Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of

Master of Applied Science

In Environmental Systems Engineering

University of Regina

By

Siyue Pan

Regina, Saskatchewan

August 5, 2016

UNIVERSITY OF REGINA

FACULTY OF GRADUATE STUDIES AND RESEARCH

SUPERVISORY AND EXAMINING COMMITTEE

Siyue Pan, candidate for the degree of Master of Applied Science in Environmental Systems Engineering**,** has presented a thesis titled, ***Saskatchewan Electrical Power Systems Planning under Stochastic Conditions and Federal Climate Change Regulations,*** in an oral examination held on August 4, 2016. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

External Examiner:	Dr. Zhou Zhang, Faculty of Business Administration
Supervisor:	Dr. Guo Huang, Environmental Systems Engineering
Committee Member:	*Dr. Chunjiang An, Environmental Systems Engineering
Committee Member:	Dr. Fanhua Zeng, Petroleum Systems Engineering
Chair of Defense:	Dr. Liming Dai, Industrial Systems Engineering

*Not present at defense

ABSTRACT

Greenhouse gas (GHG) emissions from industrial activities are the key drivers of climate change impacts in many regions around the world. In 2012, Environment Canada and Climate Change published its first GHG emissions performance standards, the *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations,* to set up the performance standards for coal-fired generation units to reduce GHG emissions in Canada. Saskatchewan is concerned about the impact of the published regulations on future electricity generation system planning and GHG. Specifically, the regulations result in a shift from existing coal-fired generation units towards other high efficient power generation units or carbon capture and storage technologies.

In this research, chance-constrained programming (CCP) and fractional programming (FP) approaches have been applied to provide recommendations and options for Saskatchewan's power system optimization, GHG emissions reduction planning, and risk analysis under the Canada *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations.* A number of policy and decision options for Saskatchewan's power system have been obtained from three designed scenarios, which are based on comprehensive consideration of the GHG emission targets, social impacts, and regional economic and environmental impacts. More importantly, multi-layer interrelationships among multiple electrical system components have been examined in this research.

ACKNOWLEDGMENT

I would like to express my gratitude to my supervisor, Dr. Gordon Huang, for his support, advice and patience throughout this study. I have enjoyed working with him in the past three years, and he has enriched my knowledge of environmental issues and provided me with a broader perspective in analyzing industrial and government environmental concerns. I would like to thank Dr. Hua Zhu for her input and suggestions on the improvement of this study. I would like also to thank my external examiner Dr. Zhou Zhang and my committee members, Dr. Fanhua Zeng and Dr. Chunjiang An for their input and suggestions, as well as Ed Dean and Vivian Dean for their assistance in formatting this thesis.

I would like to extend my gratitude to my colleagues at my job for their advice on various aspects in this study. In addition, I wish to thank my colleagues and friends in the Saskatchewan Ministry of Environment for their support that made it possible for me to pursue the completion of my Master's degree.

Finally, I would like to thank my family and my friends for their encouragement and support while I completed this study.

Table of Contents

List of Tables

List of Figures

CHAPTER 1 INTRODUCTION

1.1 Background

Greenhouse gas (GHG) emissions from industrial activities are the key drivers of climate change impacts in many regions around the world. Combustion of fossil fuels has contributed a significant amount of GHG emissions since the Industrial Revolution started in 1760, specifically the GHG emissions from coal-fired power plants. Today, coal is the largest fuel source for electricity generation and heat production through combustion in many countries (Environment Canada). In 2009, the United States Environmental Protection Agency (USEPA) announced that GHG emissions pollution threatened the health and welfare of the country. According to the USEPA GHG emissions accounting report, carbon dioxide (CO_2) is the major GHG emissions pollutant, which accounts for approximately three-quarters of global GHG emissions and 84% of U.S. GHG emissions (USEPA Clean Power Plan).

Canada is one of the 20 countries with largest GHG emissions in the world (CAIT Climate Data Explorer, 2016). The most recent of Canada National Inventory Report (NIR) indicated that Canada emitted 732 megatonnes (Mt) carbon dioxide equivalent (CO_2 eq) in 2014, which was nearly 20% above the 1990 GHG emissions level. The Government of Canada has recognized that climate change is a major threat to Canadian’s health and welfare, and has provided national and international leadership to take action on climate change. Environment and Climate Change Canada (ECCC) is developing performance standards for a number of major industrial sectors to address climate change issues. In 2012, ECCC published its first GHG emissions performance standards, the *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations* (the Regulations), to set up the federal performance standards for coal-fired power plants to reduce GHG emissions in Canada. Effective on July 1, 2015, the federal Regulations will ensure that new coal-fired units and coal-fired units past the end of their useful life will emit at a level equivalent to high-efficiency natural-gas electricity generation. This means all coal-fired power plants have to reduce the GHG emissions intensity to 420 tonnes of carbon dioxide per gigawatt hour (CO_2/GWh) at the end of their 50 years after commencement or retrofit with carbon capture and storage (CCS) equipment.

Energy system management across Canada has been a great concern, and the future system planning is a complex issue challenging decision makers. Many provinces and territories in Canada require alternatives to replace coal-fired power plants with lower GHG emission power generation, like high efficiency natural gas-fired plants, along with clean energy sources like nuclear, hydropower, solar and wind power. There are many options with which each province or territory could replace coal-fired power plants to meet the federal performance; however, there are many factors other than environmental issues that have to be considered, such as grid line upgrade, transmission investment, fuel and capital costs, variable operation and maintenance cost, social impacts, local economic impacts, and a variety of systematic uncertainties. At the national or provincial level, decision makers also face challenges from energy security concerns, including short-term energy security concerns about supply and demand balance, as well as long-term energy security concerns about affordable energy price and sustainable environment.

In Saskatchewan, coal-fired power plants are the largest source of the provincial GHG emissions. They contribute over 12 Mt of GHG emissions each year, resulting in approximately 75% of the sector GHG emissions in public electricity and heat production and 16% of the province's total GHG emissions (Canada NIR, 2016). Under the federal performance standards, Saskatchewan currently has seven units within three coal-fired power plants; in total seven units that need to reduce the GHG emissions intensity to 420 tonnes CO_2/GWh at the end of 50 years after commencement unless they install CCS.

In order to switch to low GHG emissions intensity energy sources, decision makers have to make efforts to optimize energy resources allocation and to create an effective long-term fuel switching strategy, so that a transition to a more sustainable environment can be achieved in Saskatchewan. It's always hard to make any decision in any business, no expecting electricity generation sector. Conducting on efficient system analysis of the impact of long-term fuel switching is a key element of due diligence in system planning and decision making. It gives decision makers multi-criteria decision supports, and helps them make important decisions regarding the current provincial and national Climate Change Plan.

1.2 Objectives

The objective of this research is to design sound scenarios for analyzing incremental impacts of the federal performance standards and to apply chance-constrained programming (CCP) and fractional programming (FP) approaches to provide recommendations and options for Saskatchewan's power system optimization, GHG emissions reduction planning, and risk analysis under the Canada *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations.* A number of policy and decision options for Saskatchewan's power system have been obtained, which are based on comprehensive consideration of the GHG emission targets, social impacts, and regional economic and environmental impacts. More importantly, multi-layer interrelationships among multiple electrical system components have been examined in this research.

CHAPTER 2 LITERATURE REVIEW

2.1 Energy System and Economic Models used for Energy System Planning

Fossil-fuel power plants are well known as the highest GHG emitters in the electricity generation sector. Particularly, coal-fired power plants account for the highest GHG emissions sources when compared with all other types of power plants. As climate change becomes a critical issue and concern for many governments, new performance standards for coal-fired power plants are announced in a number of countries. For instance, Canada has proclaimed the *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations* on September 12, 2012. The USEPA introduced an economic approach to develop performance standards for GHG emissions from stationary sources, and announced the *Clean Power Plan* on August 3, 2015. The European Union has also led energy policy and GHG emissions reduction plans for many years.

Today, technology is progressing rapidly; there are many options for power systems available in market within a complex societal framework. During the past decades, many research studies have been conducted in the field of power system modeling and forecasting to help decision makers analyze technical, economic and social performances of various climate change policies. Suzuki and Nijkamp (2016) developed a Target-Oriented Distance Friction Minimization model for evaluate European and A&A countries' energy-economic efficiency. The research provided an operational sustainability strategy for other countries to improve their energy efficiency. Carvalho et al. (2016) proposed a multi-objective linear programming model to evaluate the trade-off between energy, economic and environmental objective in Brazil. Mundaca et al. (2010) introduced bottom-up energy-economy models to examine energy efficiency policies and to induce the changes of new technologies. Engineering economic models were also developed to evaluate the energy supply and demand in the future; these models introduced climate change policies variables to address the environmental impact (Worrell et al. 2004).

2.2 Energy Strategies and Policies for Sustainable Development Studies in Canada

In Canada, environmental policies have become more and more stringent. In order to face future regulatory uncertainties, the use of renewable energy sources in Canada is expected to become a key solution to minimize both air pollution and GHG emissions. Sustainable development is an important objective of Canada, especially in renewable energy development. In fact, Canada is the second largest hydroelectricity generation producer in the world after China, with hydroelectricity providing 59.3 percent of Canada's total electricity generation (Canada Natural Resources). Tables 2.1 and 2.2 show the Canada federal, provincial and territorial measures to address climate change issues (Canada 2^{nd} Biennial Report, 2016). Liming et al. (2008) developed an analytical framework to investigate the policies and strategies regarding sustainable energy development. The framework examined the barriers and concerns for the existing systems, and proposed energy efficiency and renewable energy strategies. Hofman et al.

(2009) applied a regression analysis to confirm that renewable energy development is a key factor in achieving better energy efficiency in Canadian situations.

Coal-fired power plants represent a major GHG emissions source in North America. In Canada, many provinces are closing down coal-fired generation plants, replacing them with more energy efficient natural gas-fired plant, and renewable sources such as biofuel sources, nuclear, solar and wind power plants. In 2015, Ontario passed legislation to permanently ban coal-fired electricity generation units for the entire province. Carbon capture and storage (CCS) technology is another method to reduce the GHG emissions from coal-fired power plants. In 2014, SaskPower's Boundary Dam CCS project came online. It is the world's first commercial scale CCS project integrated with the coal-fired power generation unit. This project was designed to capture up to one million tonnes of CO2 each year. Bataille et al. (2015) analyzed the relationship between companies' expectation of government environmental policies and CCS project investment options in different regions. He used the economic figures to evaluate the potential CCS projects options in Alberta, Canada.

Table 2.1 Canada Provincial and Territorial Climate Change Policy Comparisons

Provincial/Territorial Measures	
Alberta	• *Specified Gas Emitters Regulation* (includes the revisions announced in June 2015), including carbon offset and technology investment systems • Alberta's renewable fuels standard • Alberta's microgeneration regulation • Alberta's bioproducer and public transit programs • Quest carbon capture and storage project • Alberta Carbon Trunk Line Project – CO_2 capture and use for enhanced oil recovery
British Columbia	• BC carbon tax • BC renewable and low carbon fuel requirements regulation • BC emissions offsets regulation • Landfill gas management regulation
Manitoba	• Manitoba's ethanol sales mandate • Manitoba's biodiesel mandate • Manitoba emissions tax on coal
New Brunswick	• New Brunswick's renewable portfolio standard
Newfoundland and Labrador	• Muskrat Falls hydro project
Nova Scotia	• Renewable portfolio standard for electricity generation • Electricity demand-side management policies • Solid Waste-Resource Management Regulations • Cap on GHG emissions from the electricity sector
Ontario	• Ontario residential electricity peak savings (time-of-use pricing) • Ontario feed-in tariff program • Landfill gas regulation (O. Reg. 216/08 and 217/08) • Ontario coal phase-out • Independent Electricity System Operator contracted electricity supply • Ontario's ethanol in gasoline rules • Ontario's greener diesel mandate • Ontario's nuclear refurbishment
Quebec	• Quebec cap-and-trade system for GHG emission allowances (includes reductions occurring in Quebec only) • Quebec's 5% ethanol objective in gasoline distributors fuel sales • Quebec's drive electric program • Landfill gas regulation
Saskatchewan	• Saskatchewan ethanol fuel program • Saskatchewan renewable diesel program • Boundary Dam Carbon Capture Project

Sources: Canada 2nd Biennial Report, 2016

Table 2.2 Canada Federal Climate Change Policy

Federal Measures
• Reduction of carbon dioxide emissions from coal-fired generation of electricity regulations
• Residential building code changes to incorporate energy efficiency for adoption by provinces across Canada
• Commercial building code changes to incorporate energy efficiency for adoption by provinces across Canada
• *Renewable Fuels Regulations*
• Commercial appliance efficiency improvements (excludes lighting)
• Residential appliance efficiency improvements, includes refrigeration, freezers, ranges and dryers
• New housing and retrofit efficiency improvements
• Facilitation of industry adoption of an energy management standard, acceleration of energy-saving investments, and exchange of best practices information within Canada's industrial sector
• Light-duty vehicles 1 (LDV-1) GHG emissions standards for the light-duty vehicle model years 2011 to 2016
• Light-duty vehicles 2 (LDV-2) GHG emissions standards increases stringency for model years 2017 to 2025
• Heavy-duty vehicles (HDV) GHG emissions standards for heavy-duty vehicle model years 2014 to 2018
• The pulp and paper green transformation program, to improve environmental performance of mills including GHG emissions reductions; the program ended in 2012 but will result in ongoing emission reductions
• Incandescent lighting phase-out

Sources: Canada 2nd Biennial Report, 2016

2.3 Optimization Modeling for Energy System Management under Uncertainty

Mathematical models have been commonly used for decision programs analysis in diverse business fields, such as finance and economic study, energy optimization, environment management, water quality management, and even for social activity planning. Optimization models have been used and applied widely to assist decision makers and policy makers in identifying solutions and making judgments based on the selected decision variables.

Stochastic mathematical programming (SMP) is a classic mathematical programming approach to solve the uncertainty problems with a given objective. Uncertain parameters are usually represented in a probability distribution function (PDF). For energy system optimization, stochastic modeling technique is a meaningful method to reflect the impacts of unpredictable cost factors based on the energy system planning decisions and potential industrial deregulation processes under national/regional regulations and a variety of uncertainties in future (Wallace et al. 2003). For example, Huang (1998) applied an inexact-stochastic water management to evaluate the water quality management within an agricultural system. Skantze et al. (2000) developed a dynamic stochastic model for analyzing the impacts of electricity price changes in a multi-market environment. In recent years, linear fractional programming (LFP) methods have been used to solve uncertain variables and parameters in engineering fields such as waste management and power system management. Zhu and Huang (2011) introduced a stochastic linear fractional programming approach for waste management. Zhu and Huang (2013) developed a dynamic stochastic fractional programming for electric power systems analysis. Zhu et al (2014) designed a fractional programming model for regional energy system study.

Chance-constrained programming (CCP) is a major SMP method, which can be applied to analyze optimization problems associated with random parameters (Brige et al. 1997). Kamjoo et al. (2016) applied CCP method to analyze the uncertainties in renewable energy system, and found that CCP is an efficient method to analyze power system. Liu et al (2016) designed an inexact two-stage chance-constrained programming model, which has been used to analyze northern China's coal-fired facilities under the regulated coal-pricing mechanism. The model contains multiple scenarios to provide different options for decision makers. Wang et al (2011) developed a chance-constrained two-stage stochastic program model to the maximize wind power output under the commitment problem. The proposed method was successfully used for power system optimization. Olson et al. (1987) applied the CCP method to analyze the uncertainty factors based on the given prescribed confidence level. Li et al. (2007) developed an inexact two-stage chance-constrained program model for waste management system planning.

2.4 Literature Review Summary

Mathematical programming methods have been successfully applied to many researches and practical problems in many fields to solve the complex uncertainty issues. Today, energy system management is becoming more complex and challenging than before. Uncertainties associated with international, national and local environmental regulations became new criteria used by many decision makers to design long-term uninterrupted availability of energy systems both at affordable cost and in an environmentally sustainable manner.

Saskatchewan has three coal-fired power plants in total seven units that will be affected under the Canada federal performance standards. Saskatchewan decision makers have to decide on either shutting down or retrofitting to CCS the existing coal-fired units in the next 10 to 20 years. In this research, chance-constrained programming and fractional programming techniques have been applied for an optimization case study in Saskatchewan regarding coal-fired power unit regulation and electrical system planning that is being affected by the Canada *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations*.

CHAPTER 3 SCENARIOS DESIGN FOR SASKATCHEWAN ELECTRICAL SYSTEM PLANNING

Globally, coal-fired power plants are generating over 40% of the total electricity. As of today, coal-fired power plants are emitting 30% to 40% of GHG emissions around the world (Balat, 2007). Coal-fired power plants are being used as the majority power generation in poor and developing countries. In the United States, GHG emissions emitted from fossil fuels combustion count 78% to 95% of the total. All United States' coal-fired power plants alone emitted 81% of the total GHG emissions associated with electricity generation (Kim et al., 2005). In Saskatchewan, coal-fired generation contribute over 50% of the annual electricity generation. The GHG emissions from fossil-fuel combustion account for approximately 75% of total provincial GHG emissions covered under the Kyoto Protocol.

Many researches have provided scientific evidence that the major GHG emission sources contributing to climate change issues are from coal use in energy generation. Burt et al. (2013) indicated that human health could be harmed by the GHG emissions emitted from coal-fired power plants, which are a major cause of the global temperature increases. Since the Industrial Revolution started in 1760, earth's average surface temperature has been increased by 2 °C. Climate change issues have become a major worldwide health threat today. The U.S. Environmental Protection Agency (USEPA) indicated that both the public health and the public welfare, now and in the future, could be endangered by GHG emissions (Federal Register/ Vol. 74, No. 239). Yang et al. (2007) applied a life cycle assessment (LCA) method to measure the environmental impacts from 13 power plants in Taiwan. The results indicated that coal-fired plants are neither economic nor environmentally friendly in a long-term perspective compared with other power plants with high-energy efficiency.

Climate change is a worldwide challenge and Canada recognizes the issues needed for action at both mitigation and adaptation levels. Canada has been involved in most meetings of the United Nations Framework Convention on Climate Change. Canada's most recent action was signing the Paris Climate Change Agreement in December 2015, which committed to reduce GHG emissions by 30% below 2005 base year by the end of 2030. ECCC is developing a sector-by-sector regulatory approach to reduce GHG emissions to achieve their target. The most recent examples of the regulatory approach are:

- In April 2010, ECCC developed the renewable fuel requirement for gasoline, diesel and heating oil;
- In Jun 2010, ECCC proposed the GHG emissions reductions from coal-fired generation units;
- In October 2010, ECCC developed the emission standards for light duty vehicles for model years 2011 to 2016;
- In March 2015, Canada and the United States proposed a joint statement to reduce methane emissions from upstream oil and gas industry.

This Chapter provides the scenarios design for Saskatchewan's electrical system planning, based on the background information of the *Canada's Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations,* Saskatchewan macroeconomic details, Saskatchewan’s electricity generation characteristics, and urgent future power system planning decisions for Saskatchewan.

3.1 Framework of Canada’s *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations*

In June 2010, ECCC announced its intention to regulate GHG emissions from coal-fired generation units. Then the *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations* (the Regulations) came into force on 1st July, 2015. The ECCC regulations require all existing and new coal-fired electricity generation units to meet a fixed performance standard at 420 tonnes CO_2 /GWh. The proclaimed regulations include:

- Coal-fired electricity generation units commencing before 1970 will be affected in the earlier of 2019 or end of the year 50 years after commencement;
- Coal-fired electricity generation units commencing after 1974 but before 1986 will be affected in the earlier of 2029 or end of the year 50 years after commencement;
- Coal-fired electricity generation units commencing after 1985 will be affected at the end of the year 50 years after commencement;
- The new and existing coal-fired electricity generation units can choose to install carbon capture and storage system, and will provide an extra 5 years for the unit to meet the performance standard.

Under the federal regulations, coal-fired electricity generation units' performance standards and the retirement and shutdown timelines have been declared. In order to comply with the regulations and meet the growing demand for provincial power generation, Saskatchewan has to decide on the new types of electricity power plants that need to be built after coal-fired generation units' shutdown, as shown in Table 3.1.

Table 3.1 Saskatchewan Coal-fired Generation Unit Retirements Schedule

Plant Name	Unit	Commissioned Year	Retirement Year
Boundary Dam	1	1959	Closed (2014)
	2	1959	Closed (2015)
	3	1970	CCS, Ongoing
	4	1970	2019
	5	1973	2019
	6	1977	2027
Poplar River	1	1981	2029
	2	1983	2029
Shand	1	1992	2042
Total Units	9	-	-

3.2 Saskatchewan Macroeconomic Conditions

Saskatchewan, one of three Prairie Provinces in Canada, accounts for 647,797 km^2 or 6.5% Canada's total area of 9,984,670 km^2, as shown in Figure 3.1. Saskatchewan has the eighth largest land area of Canada, with 553,556 km^2 of lands, including drylands (as well). As of September 2015, Saskatchewan has a total estimated population of 1,133,637, increased 12% from 1990 (Statistics Canada, 2016). Nearly half of the residents live in the province's two largest cities, Saskatoon and the provincial capital, Regina. Some other Saskatchewan major cities include Price Albert, Moose Jaw, Yorkton, Swift Current, North Battleford and Estevan.

Saskatchewan is one of the most resource-rich provinces in Canada. A large portion of its economy is significantly influenced by the global commodity prices, and its agriculture is affected by the climatic impacts as well. Saskatchewan has some of the most productive lands in the world, and it is a major exporter of agricultural products. In 2014, the total crop production was 30,514,500 tonnes, and the total net farm cash income was $4.626 billion. In Canada, Saskatchewan is the second largest crude oil production province behind Alberta, and it is the largest potash and uranium production province. In 2014, the industry of mining, oil and gas contributed $12.4 billion in revenue to the province, accounting for 21% of the provincial total real gross domestic product (GDP). Overall, Saskatchewan's GDP was $59.3 billion in 2014, which makes it one of the top five provinces in terms of economic growth in Canada (Saskatchewan Economic Review, 2014). According to Statistics Canadas's median total income data by family type, released on June 26 2015, Saskatchewan's household income was $82,990 in 2013, which was the fourth highest among the provinces and territories of Canada.

Figure 3.1 Geographical Reference Map for Saskatchewan (Google Map, 2016)

3.3 Overview of the Electricity Generation Sector in Saskatchewan

The electricity generation sector in Saskatchewan has played an important role in supporting the provincial economic activities. Similar to most other provinces and territories in Canada, the electricity generation sector is regulated by the governments. SaskPower is the principal power producer in Saskatchewan. The company belongs to the provincial government through its holding company, the Crown Investment Corporation.

In 2013, Saskatchewan's electricity generation sector produced 4,500 GWh through its hydroelectric facilities, 17,200 GWh through its coal-fired and natural gas-fired units, and 700 GWh through its wind facilities. Saskatchewan's total electricity generation in 2013 was 23,100 GWh, which amounted to approximately 3.8% of Canada total (Statistics Canada, 2016).

Saskatchewan has diverse power generation options to balance the system. As of 2016, Saskatchewan has 28 large-scale power generation plants along with a few small-scale power generation plants. Specifically, there are 17 power plants owned and operated by SaskPower, including 7 hydroelectric power plants,, 5 natural gas-fired power plants, 3 coal-fired power plants and 2 wind power plants. In addition, there are 4 natural gas-fired power plants, 4 waste heat power plants and 3 wind power plants operated by independent power producers, who have long-term agreements with SaskPower to sell their power generation. In 2014, Saskatchewan's total available generating capacity was 4,204 MW. Table 3.2 shows Saskatchewan has mixed electricity generation options in Canada, and Figure 3.2 shows Saskatchewan's potential power mix options in the future.

Table 3.2 Power Generation Options Comparisons between Canada and Saskatchewan

	Canada	Saskatchewan
Solar	X	X
Tidal	X	
Wind	X	X
Combustion Turbine	X	X
Internal Combustion	X	X
Nuclear	X	
Conventional Steam	X	X
Hydro	X	X

Source: Canadian Electricity Association, 2016

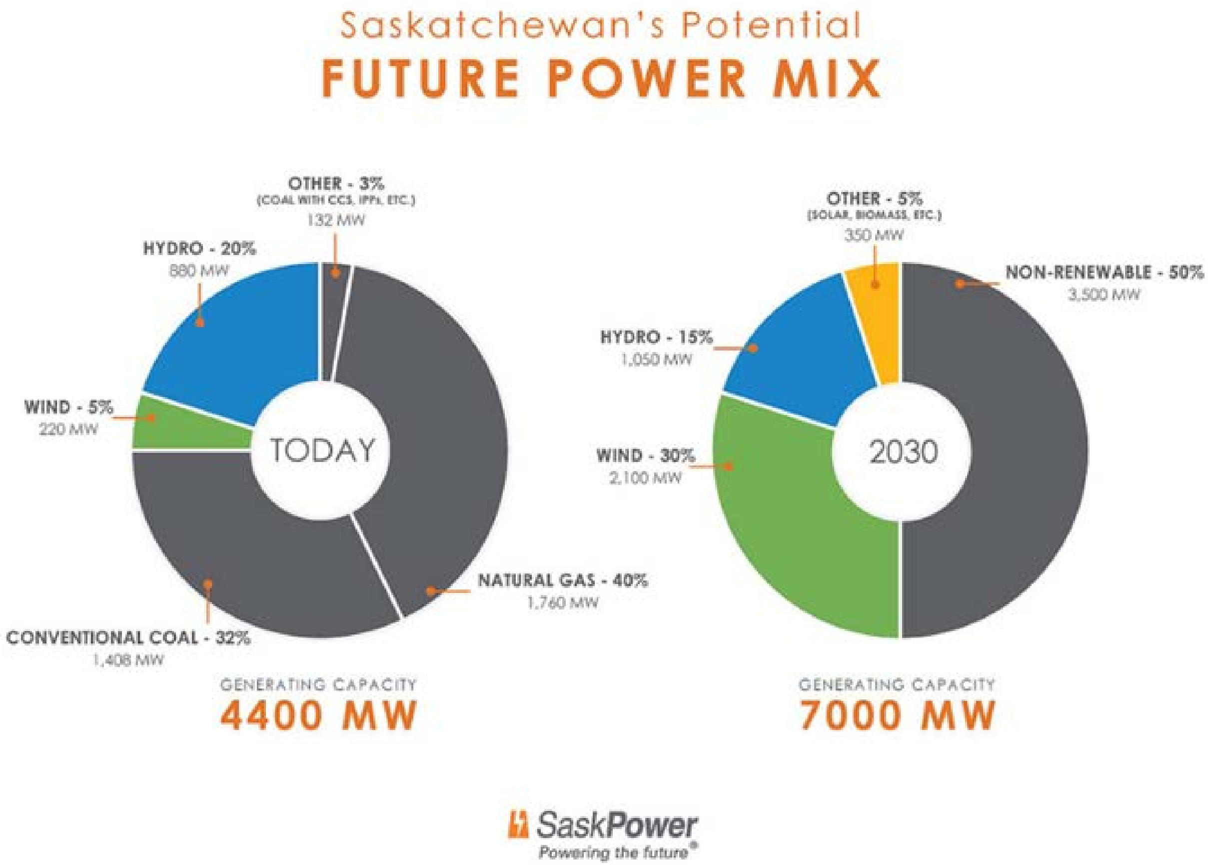

Figure 3.2 Saskatchewan's Potential Future Power Mix (SaskPower, 2014)

3.4 Saskatchewan's GHG Emissions

Canada's 2016 NIR indicated that Saskatchewan had GHG emissions growth of 68% from 1990 to 2014, which is the highest among Canada provinces and territories. In contrast, Canada's average GHG emissions had also increased by over 20%, while the second highest province, Alberta, had GHG emissions growth of 56% during the same period. In 2014, Saskatchewan had the highest per capita GHG emissions in Canada, reaching 67 tonnes CO_2eq per person. Saskatchewan also had the highest per capita GHG emissions compared with the top 20 countries in the world (SaskWind, 2010).

Saskatchewan's electricity generation sector's GHG emissions have increased by 27.6% from 11.2 Mt CO_2eq in 1990 to 14.3 Mt CO_2eq in 2014 due to rapid growth in electricity demand. In 2014, the electricity generation sector's GHG emissions accounted for 19% of total Saskatchewan GHG emissions. At present, Saskatchewan's 3 coal-fired generation facilities' GHG emissions account for nearly 80% of total Saskatchewan's electricity generation sector GHG emissions (Environment Canada, 2016).

Canada's 2016 Second Biennial Report on Climate Change predicted that Saskatchewan's GHG emissions would be 75 Mt CO_2eq in 2020 and 73 Mt CO_2eq in 2030. The report indicated that western Canada's oil and gas sector was the fastest growing source of GHG emissions in Canada and that its climate change footprint would be greater than those of all provinces except for Ontario in 2020 and 2030 projection years. Saskatchewan's economy is industrial and agricultural activities based, and the provincial economy will be expected to have continuous growth to 2020 compared to 1990 levels. Figure 3.3 shows Saskatchewan has the highest GHG emissions growth rate since 1990 and Figure 3.4 shows Saskatchewan has the highest per capita GHG emissions in Canada. Figure 3.5 shows the most significant GHG emissions sources from Saskatchewan electricity sector are the three coal-fired generation power plants, and Figure 3.6 shows the electricity sector is the one of the major sectors contributing to GHG emissions in Saskatchewan. Therefore, achieving the GHG emissions reduction target is a challenge for Saskatchewan under the current climate change actions.

Saskatchewan will have to ensure that GHG emissions reduction targets for all coal-fired generation units are met within the next 30 years in accordance with the federal performance standards. Without shutting down the existing large-scale coal-fired generation units, biomass cofiring and CCS are the two most available options to achieve the federal performance standards. However, the cost of biomass cofiring is significantly higher in Saskatchewan, due to the limited bio fuel sources located nearby the provincial coal-fired generation units. The capital cost for CCS is also very high due to the fact that the technology is relatively new and still in development. In addition, the world oil price dropped significantly over the past couple of years, resulting in a low demand for CO_2 in EOR processes. Due to the above reasons and considerations about overall cost, technologies availability, power output reliability and environmental compliance factors, this research will only choose natural gas-fired, hydropower, solar and wind power as the power sources for future capacity expansion options.

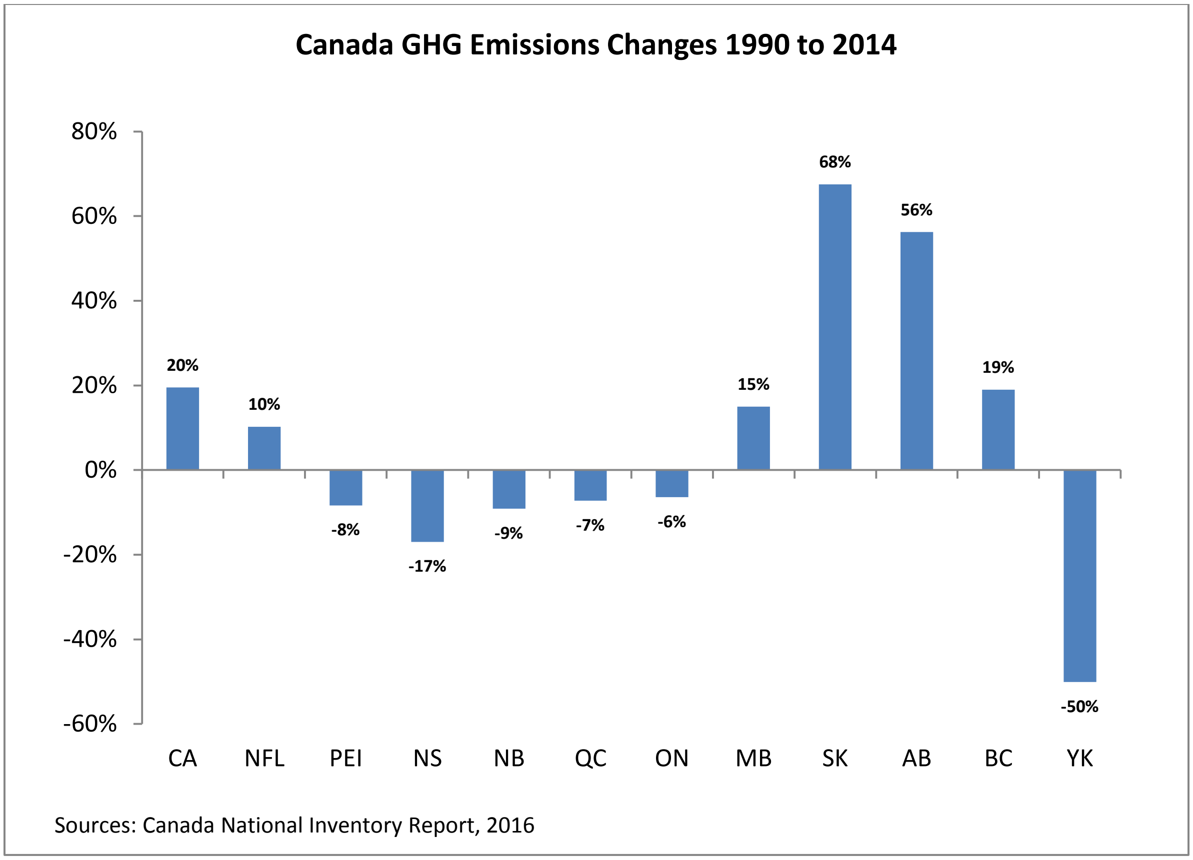

Figure 3.3 Canada GHG Emissions Changes from 1990 to 2014

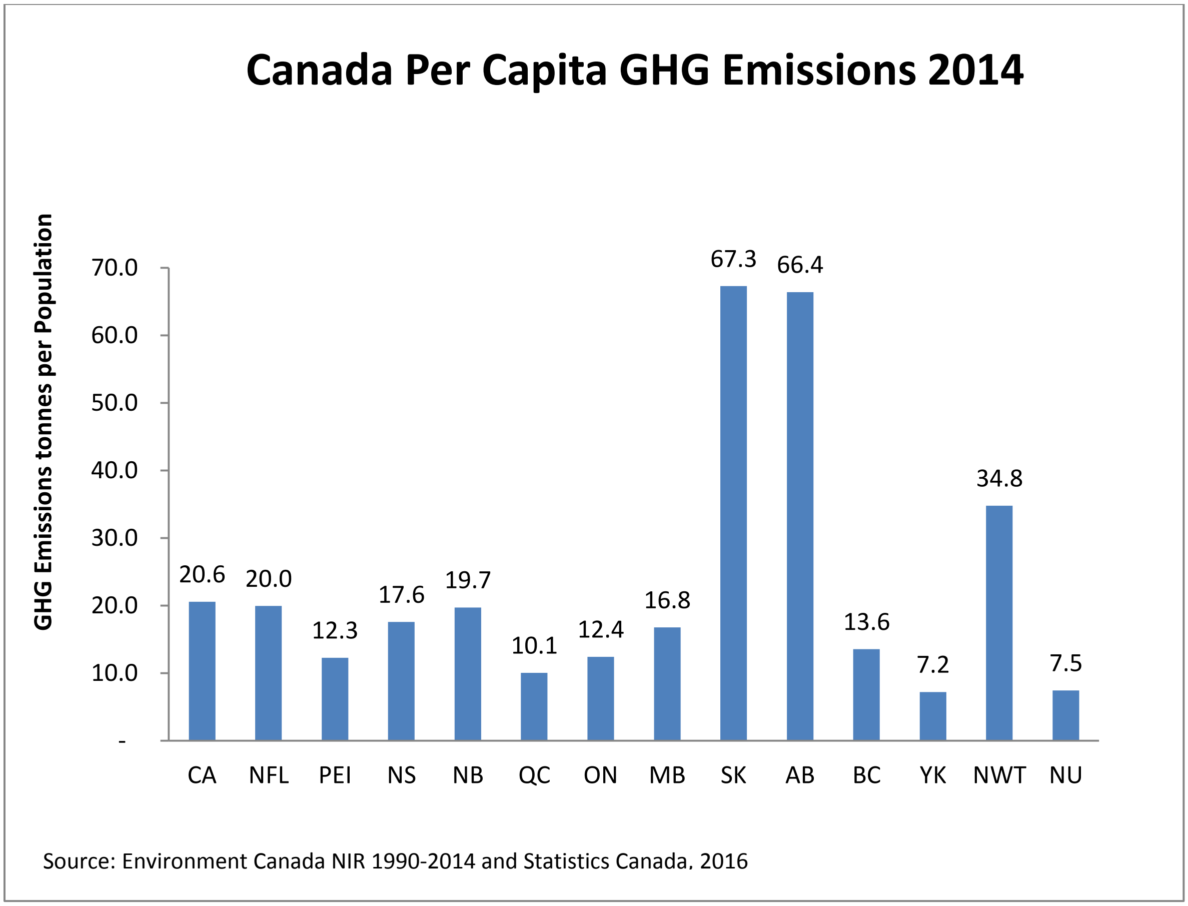

Figure 3.4 Canada Per Capita GHG Emissions, 2014

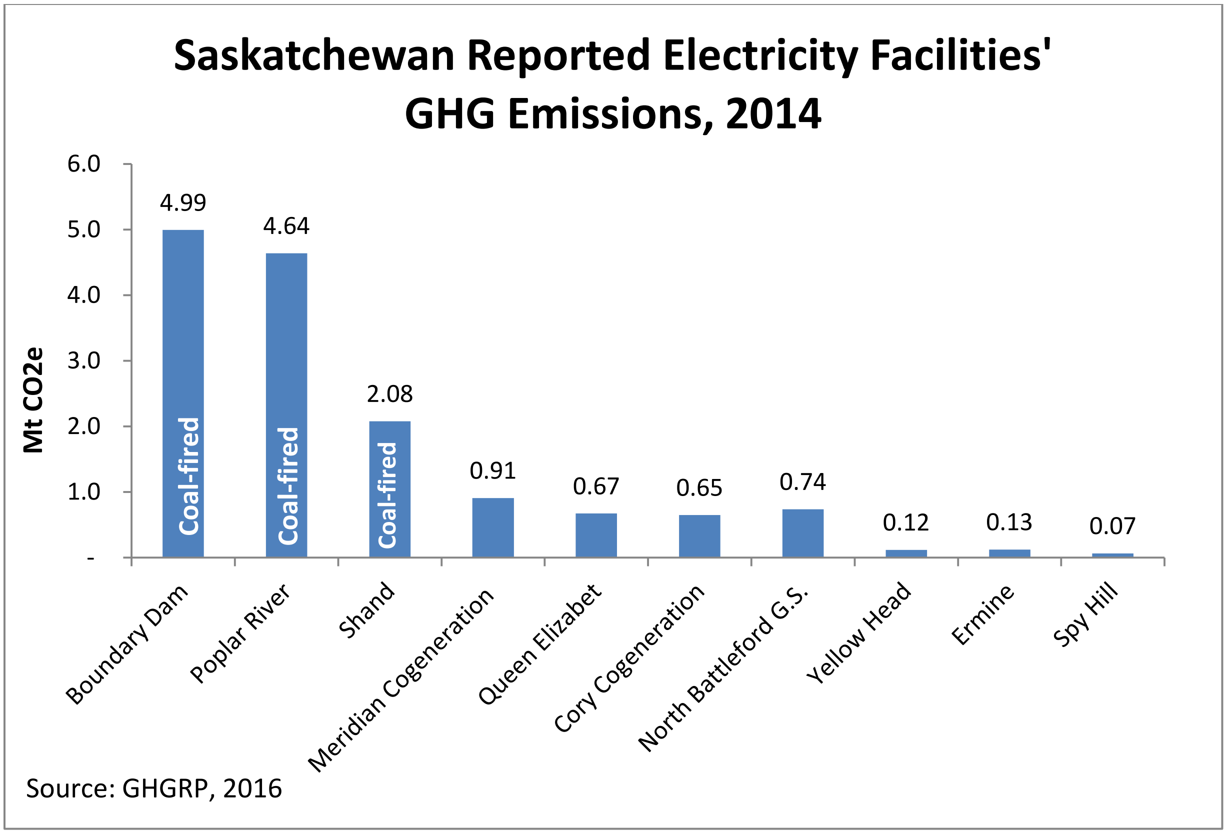

Figure 3.5 Saskatchewan 2014 Reported Power Generation Facilities' GHG Emissions

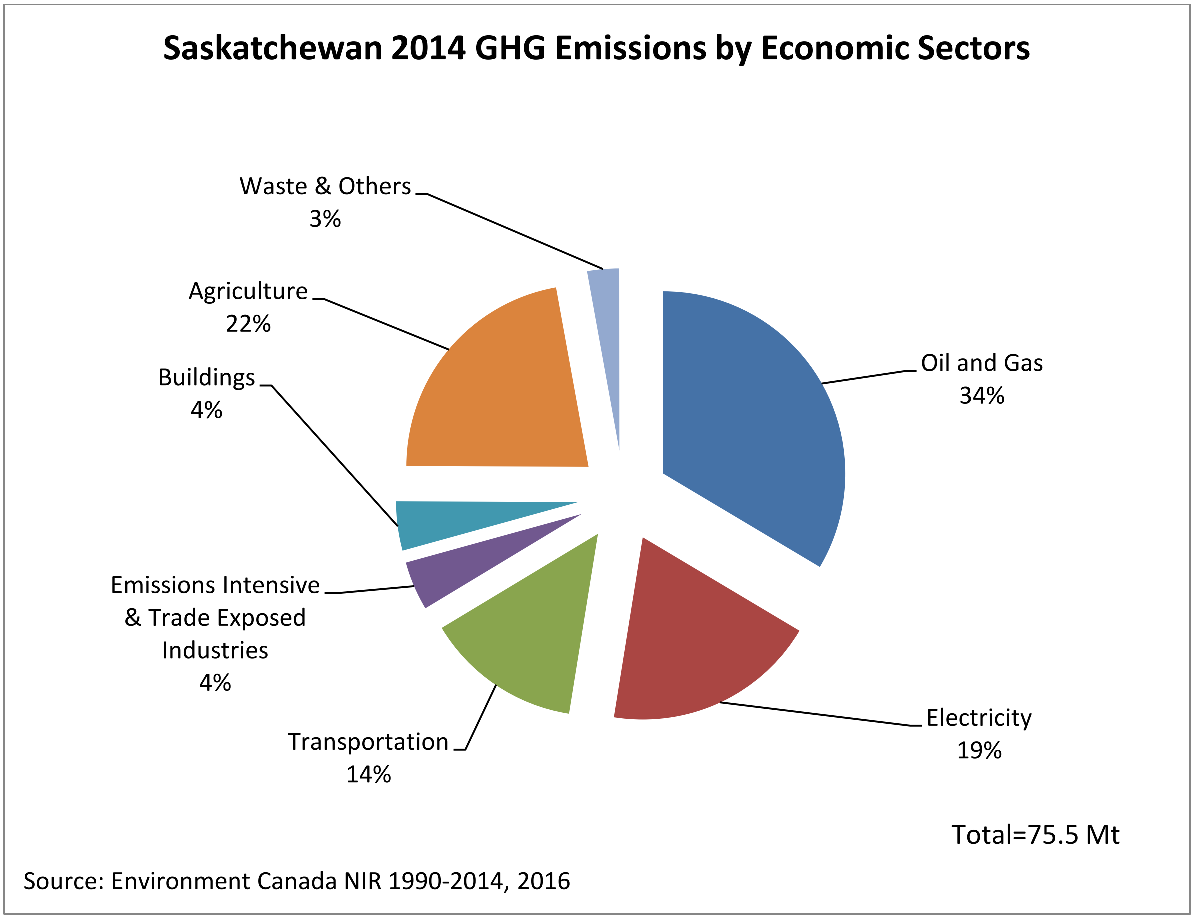

Figure 3.6 Saskatchewan 2014 GHG Emissions by Economic Sectors

3.5 Economic and Environmental Impacts of the Canada's Coal-fired Generation Performance Standard in Saskatchewan

The upcoming federal *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations* (the Regulations) is leading Saskatchewan coal-fired generation units toward a sense of urgency to comply with the new regulations. Under the Regulations, Boundary Dam Units 4 and 5 would need to shut down by the end of 2019, Boundary Dam Unit 6, Poplar River Units 1 and 2 would need to shut down by the end of 2029, and Shand would need to shut down by the end of 2042. The options for replacing the affected coal-fired generation units include retrofitting with CCS technology to meet the regulations, or with other high efficiency power generation units.

This poses a problem for decision makers since all of Saskatchewan's coal-fired generation units reach the end of life in the next 20 years. The decisions take time and have to be made with such caution, since the coal-fired power generation units are the majority of the provincial baseload power supply. In addition to coal-fired regulatory processes, Saskatchewan is currently pursuing CCS options to mitigate the GHG emissions problem greatly. The Government of Saskatchewan has installed a CCS project at the unit 3 of Boundary Dam Power Plant, which expects 1 Mt of CO_2 to be captured, stored and then sold to upstream oil companies for enhanced oil recovery (EOR) processes. Since global oil prices have fallen significantly from $110 per barrel in 2011 to below $60 per barrel in 2016, Saskatchewan is facing fewer new investments in the upstream oil industry, and this also is affecting the production level of existing oil companies. The oil price is one of the key factor to evaluate whether using CO_2 for EOR processes is economic-efficient or not. Canada's current carbon pricing is in the range of

$15 to $30 per tonne of carbon. Therefore, using CO_2 for EOR processes is a very expensive way to increase the oil production in the current low oil price market.

It is urgent for analyzing the current electricity generation system for Saskatchewan, and developing effective strategies to ensure that the future GHG emissions will achieve the federal performance standards.

3.6 Scenarios Design for Saskatchewan's Electrical System Planning

Coal-fired electricity generation has been one of the major GHG emissions sources in Saskatchewan. In 2014, coal-fired electricity generations accounted for 32% of the total generating capacity, but contributed over 81% of the electricity sector GHG emissions (2016 Canada NIR). The federal performance standards require all Saskatchewan coal-fired electricity generation units to meet a fixed performance standard at 420 tonnes of carbon dioxide per gigawatt hour (CO2/GWh). The trade-offs between environmental and economic implications are not avoidable in power generation industry. Accordingly, decision makers have to make investment decisions within the next 20 years for further power system planning. They have either to replace the existing coal-fired units to high efficiency natural gas-fired power plants, or use other low-carbon and green technologies as alternatives, such as co-generations, hydro, nuclear, wind, and solar power generation. At the provincial level for policy development, Saskatchewan must meet federal regulatory standards for the coal-fired generation units. Otherwise, the province will have significant challenges to meet the aspirational GHG emission reductions target.

Accordingly, strategic decisions on the electricity system transition are becoming a great challenge in Saskatchewan as environmental regulations are becoming more stringent.

Today, there are many electricity supply options available in the market, but not all types could meet the minimum baseload and peak conditions. For instance, solar power facilities emit no GHG emissions, but they cannot deliver enough power generation within a specific given time period to meet the real peak demand. Hydropower facility relies heavily on local climatic condition, location, and river flow rate. Grid energy storage is not an economical option for commercial scale level. Table 3.3 shows the detailed comparison of different electricity supply options in Saskatchewan.

An optimization model is desired to analyze both cost-competitive and environmental regulations options for Saskatchewan electricity system planning. The detailed assumptions for scenario design are based on the generation growth, capacity factors and emission factors for different types of power plants, coal-fired generation retirements under the federal regulations, coal-fired retrofits for CCS, and future electricity demand. Three system planning scenarios have been designed to help decision makers compare the cost for different technologies and benefits of environmental regulations under different climate change policies. The entire 20-years planning horizon has been divided equally into 4 study periods of five years each. Over the planning horizon, the following strategies of replacing the existing coal-fired generation units are considered in all three proposed scenarios:

- Retrofit to CCS for Boundary Dam Unit 3 (already implemented);
- Increase generation from new high efficiency natural gas-fired generation ;
- Increase hydroelectricity imports from Manitoba;
- Increase renewable generation from new wind and solar generation.

Table 3.3 Available Electricity Supply Options in Saskatchewan

Saskatchewan Power Options	Advantages	Disadvantages
Biomass (baseload)	• Renewable Energy source • Reduces material going to landfills	• High transportation costs • Technology is still developing
Coal with CCS (baseload)	• Low GHG emissions • Potential for low-cost electricity	• Technology is still developing • Higher Capital cost
Cogeneration-Natural Gas (baseload)	• Lower GHG emissions • Proven technology	• Less operating flexibility • Non-renewable fuel source
Geothermal (baseload)	• Low fuel costs • Renewable source of energy	• High construction costs • Best suited to particular geographic regions
Hydro reservoir/run-of-river (baseload, peak/intermediate/intermittent)	• Low GHG emissions • Low operation costs • Renewable power sources	• High construction costs • Impacts on local habitat
Imported electricity (peak, baseload)	• Low GHG emissions • Reliable	• Cost is variable • Additional transmission is required
Natural gas-simple cycle gas turbine (peak, baseload)	• Lower GHG emissions than conventional coal • Low capital costs	• Low efficiency • The availability and cost of natural gas are potential risk
Natural gas-combined cycle gas turbine (intermediate, baseload)	• More efficient than simple cycle gas turbines • Lower GHG emissions than conventional coal and simple cycle	• The availability and cost of natural gas are potential risks • Non-renewable fuel source
Nuclear-small modular reactor (baseload)	• Low GHG emissions • A reliable and stable source of baseload power	• Uncertainty surrounding long-term cost of decommission, spent fuel and waste storage
Solar (intermittent)	• No GHG emissions • Can be used for small-scale remote operations outside of the power grid	• Cost is considerable • Limited capacity due to intermittent supply
Wind (intermittent)	• No GHG emissions • Clean and renewable energy source	• Intermittent supply • Cannot increase or decrease output according to demand

Sources: SaskPower Customer Guide to the SaskPower system, 2012

3.6.1 Scenario 1: Basic regulation scenario

This scenario involves a cost minimization analysis under minimum requirements of the federal performance standards. Since the federal performance standards only require coal-fired generation units to be operated below an emission intensity level of 420 tonnes CO2/GWh, there is no other GHG emissions standards in place for power plants using other types of generation technologies. Therefore, Saskatchewan may choose to shut down all existing coal-fired units except BD3 with CCS and to fill the capacity gap by building relatively cost-effective natural gas-fired units. This option could avoid extra cost beyond federal performance standards and also could achieve acceptable environmental outcomes under current basic regulations. In other words, this scenario would not impose any restrictions on total GHG emissions, or any requirements for renewable energy development.

3.6.2 Scenario 2: Optimal-cost scenario

This scenario accommodates the requirements under the federal coal-fired electricity standards, and promotes the use of renewable energy options. Under this scenario, high efficiency natural gas-fired power plants would be used as primary baseload and intermediate, but with a ceiling of the maximum expansion. Several renewable electricity generation technologies would be used to meet the intermediate electricity demand and achieve a certain percentage for ensuring better environmental outcomes than basic regulation scenario.

3.6.3 Scenario 3: Optimal-efficiency scenario

This scenario not only accommodates the requirements under the federal coal-fired electricity standards, but also promotes maximization of GHG emissions reduction with the minimization of environment impact in a most economical way, leading to stringent use of all types of fossil fuel sources.

CHAPTER 4 CASE STUDY FOR SASKATCHEWAN ELECTRICITY GENERATION SECTOR MANAGEMENT

4.1 System Characterization

(1) Net Capacity and Generation

Saskatchewan is one of Canada's fastest economically growing province. Due to the growing economy and population, the electricity demand is expected to increase by 2.9 per cent in the next 20 years (2012 Customer Guide to the SaskPower System). Figure 4.1 and Table 4.4 have indicate the projected Saskatchewan net capacity availability and demand by 2035. The estimations were based on Saskatchewan's potential future power capacity (SaskPower 2014 Annual Report). It shows that an additional net capacity of more than 3,000 MW will be required between now and 2035. Table 4.2 indicates Saskatchewan's projected existing generation capacity within the next 20 years. Since Saskatchewan signed the hydropower capacity import agreement with Manitoba, therefore the projected hydropower capacity will be increased 100 MW from the first period to the second period. The estimated generation capacity expansion options for different types of power generation sources for the next 20 years are shown in Table 4.3. Since renewables could not provide baseload and peaking power for the demand side, renewable expansion constraints have been set up in Table 4.5.

(2) Cost

Electricity generation and capital cost are shown in Table 4.1, and average capacity factors for each type of power plant are displayed in Table 4.6. Both estimations were based on 2014 SaskPower Annual Report and the U.S. Average Levelized Costs for Plants Entering Service (USEPA Annual Energy Outlook, 2015).

The specific estimates presented in this case study provide the reasonable approximation of these impacts using the best available data and projections at the time the analysis was undertaken.

(3) GHG Emissions

In Canada, Saskatchewan is ranking one of top province with the largest GHG emissions from the electricity sector (2016 Canada NIR). Different electricity generation technologies have different levels of GHG emissions intensity. Since hydro, solar, wind and other renewables are non-GHG-emitting sources, combustion-based electricity generation is the major contributor of GHG emissions for the electricity sector.

ECCC GHG Emissions Quantification Guidance indicated that emission factors are the most common approach to estimate the GHG emissions at the provincial and national level. The estimated average coal-fired emission factor of 1100 tonnes CO_2/GWh has been applied to calculate the GHG emissions for all four time periods. The estimations were based on the current coal-fired generation units' annual GHG emissions (ECCC GHGRP, 2016) and the total energy output per year (Statistics Canada RESDC, 2016). For future GHG emissions assessment, the emission factor of 420 tonnes CO_2/GWh can be applied for future fleet-wide natural gas-fired generation units, which assumes natural gas-fired units have emission intensity requirements equivalent to coal-fired generation units under federal performance standards.

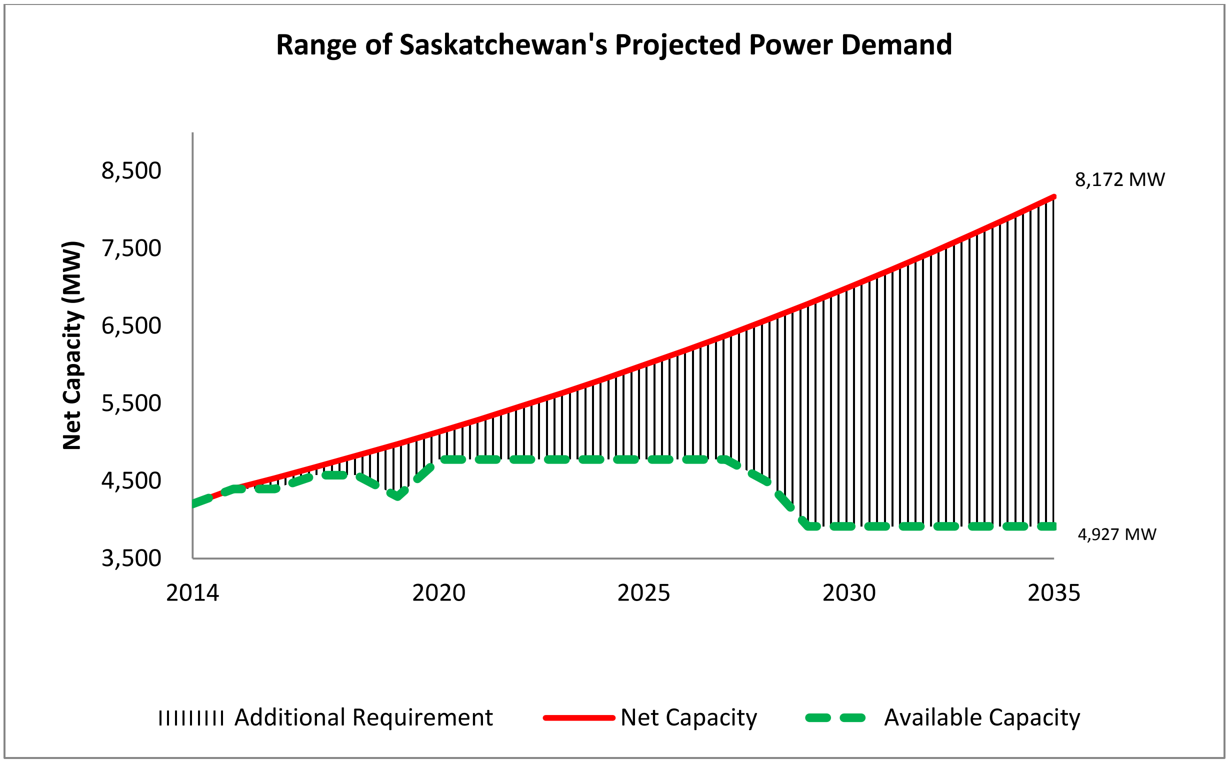

Figure 4.1 Estimated Range of Saskatchewan's Projected Power Demand by 2035

Table 4.1 Electricity Generation and Capital Cost

	Time period			
	$k = 1$	$k = 2$	$k = 3$	$k = 4$
Electricity generation cost, C_{jk} ($/MW):				
Coal ($j = 1$)	4.47	4.47	4.47	4.47
Natural gas ($j = 2$)	1.81	1.81	1.81	1.81
Hydropower ($j = 3$)	4.18	4.18	4.18	4.18
Solar ($j = 4$)	12.46	12.46	12.46	12.46
Wind ($j = 5$)	13.86	13.86	13.86	13.86
Capital cost for power-generation facilities, E_{jk} ($/MWh):				
Natural gas ($j = 2$)	15.30	14.56	13.85	13.14
Solar ($j = 4$)	120.00	111.25	103.15	95.04
Wind ($j = 5$)	62.47	63.77	65.09	66.42

Table 4.2 Existing Capacity of Power-generation Technology

	Time period			
	k = 1	*k* = 2	*k* = 3	*k* = 4
Existing Capacity , EC_{jk} (MW):				
Coal (*j* = 1)	1418.8	1252	848.8	386
Natural gas (*j* = 2)	1589	1589	1589	1589
Hydropower (*j* = 3)	864	964	964	964
Solar (*j* = 4)	2	2	2	2
Wind (*j* = 5)	221	221	221	221

Table 4.3 Capacity Expansion Options for Power-Generation Facilities

		Time period			
		$k = 1$	$k = 2$	$k = 3$	$k = 4$
Capacity expansion options, V_{jmk} (MW):					
Natural gas ($j = 2$)	$m = 1$	150	150	150	150
	$m = 2$	275	275	275	275
	$m = 3$	350	350	350	350
Solar ($j = 4$)	$m = 1$	2	2	2	2
	$m = 2$	7.5	7.5	7.5	7.5
	$m = 3$	15	15	15	15
Wind ($j = 5$)	$m = 1$	170	170	170	170
	$m = 2$	260	260	260	260
	$m = 3$	350	350	350	350

Table 4.4 Electricity Demand

	Time period			
	$k = 1$	$k = 2$	$k = 3$	$k = 4$
Electricity demands (MWh):				
$p_i = 0.01$	25,985,249	28,332,294	30,891,329	33,681,502
$p_i = 0.05$	25,728,795	28,052,676	30,586,456	33,349,091
$p_i = 0.1$	25,592,095	27,903,629	30,423,946	33,171,904

Table 4.5 Renewable Expansion Limits

Renewable Expansion Limits (MW)	p_i = 0.01	p_i = 0.05	p_i = 0.1
Solar (j = 4)	52	57.22	60.00
Wind (j = 5)	1310	1,368.71	1,400.00

Table 4.6 Average Capacity Factor (%) for each type of Power Plant

Capacity Factor	
Coal (j = 1)	0.85
Natural gas (j = 2)	0.87
Hydropower (j = 3)	0.54
Solar (j = 4)	0.2
Wind (j = 5)	0.36

4.2 The SF-ESP model for Saskatchewan Power Systems Planning

This Study intends to find the balance between the better environmental outcome and the economic development, and minimize the conflict between each other. Therefore, a Stochastic Fractional Electrical System Planning (SF-ESP) model is proposed for analyzing the impacts of the federal coal-fired generation performance standards on Saskatchewan's electrical system.

In Saskatchewan, the current options for baseload electricity sources are conventional coal-fired in association with natural gas-fired, coal with CCS and hydroelectric. The major cost-competitive option for intermediate electricity sources is wind power in association with small hydro and solar power. In the study, multiple power generation technologies potions and multiple periods exist, where applied the developed techniques of chance-constrained programming (CCP) and mixed integer linear programming (MLP) are integrated into a linear fraction programming (LFP) framework (Zhu et al. 2014). Thus, the following indices will be used:

j: Power-generation technologies (j = 1, 2, …, 5);

k: Time periods (k = 1, 2, 3, 4);

m: Capacity-expansion options (m = 1, 2, 3).

The decision variables include:

X_{jk}: Electricity generation by technology j in period k (MWh);

Y_{jmk} : Integer variable (= 1 or 0) representing whether capacity expansion for technology *j* with option *m* in period *k* will be installed or not.

Three significance levels of p_i (p_i = 0.01, 0.05 and 0.10) have been considered in this case study to allow admissible probability of violating the constraint i. Since higher p_i means higher risk, therefore decision makers can decide the different p_i levels based on their confidence level. The model solutions under different p_i levels also provide post-optimization analysis as well.

According to the 20-year deal between Manitoba Hydro and SaskPower (2015), the imported hydroelectricity capacity has already been determined, which is integrated in the model through using an increased existing capacity of hydro for the future periods. Since there is no suitable site for building large-scale hydro projects in Saskatchewan, this model doesn't consider capacity expansion of hydroelectricity.

The study horizon is from 2015-2035, in total 20 years.

The system cost is formulated as a sum of the following:

1) Costs for primary energy supply:

$$C_1 = \sum_{j=1,2,5} \sum_{k=1}^{4} 5 \cdot P_{jk} \cdot X_{jk} \tag{4.2a}$$

2) Costs for operation and maintenance

$$C_2 = \sum_{j=1}^{5} \sum_{k=1}^{4} 5 \cdot \mathrm{C}_{jk} \cdot X_{jk} \tag{4.2b}$$

3) Capital costs for capacity expansions

$$C_3 = \sum_{j=2,4,5} \sum_{m=1}^{3} \sum_{k=1}^{4} E_{jmk} \cdot V_{jmk} \cdot Y_{jmk} \tag{4.2c}$$

where:

P_{jk} = average cost for primary energy supply from technology *j* in period *k* ($/MWh);

C_{jk} = average variable and maintenance cost for generating electricity from technology *j* in period *k* ($/MWh);

E_{jk} = capital cost for capacity expansion of technology *j* within period *k* ($/MW);

V_{jmk} = capacity expansion for technology *j* with option *m* in period *k* (MW).

So the system cost is:

$$C = C_1 + C_2 + C_3 \tag{4.2d}$$

The total GHG emission reduction is formulated as:

$$G = \sum_{j=1}^{5} \sum_{k=1}^{4} 5 \cdot X_{jk} \cdot RF_j + 20 \cdot CCS \cdot (RFC - RF_1) \tag{4.2e}$$

where:

RF_j = GHG reduction factor for technology *j* compared to the national standard (i.e. 0.420 tonne CO_2/MWh) (tonne/MWh);

CCS = annual electricity generation by coal-fired technology with CCS (MWh);

RFC = GHG reduction factor for CCS-based coal-fired power generation technology compared to the national standard (tonne/MWh);

Thus, the ratio objective of SF-ESP model can be formulated as follows:

$$\text{Max } f = \frac{G}{C}$$

$$= \frac{\sum_{j=1}^{5}\sum_{k=1}^{4} 5 \cdot X_{jk} \cdot RF_j + 20 \cdot CCS \cdot (RFC - RF_1)}{\sum_{j=1,2,5}\sum_{k=1}^{4} 5 \cdot P_{jk} \cdot X_{jk} + \sum_{j=1}^{5}\sum_{k=1}^{4} 5 \cdot \mathrm{C}_{jk} \cdot X_{jk} + \sum_{j=2,4,5}\sum_{m=1}^{3}\sum_{k=1}^{4} E_{jmk} \cdot V_{jmk} \cdot Y_{jmk}} \quad (4.2f)$$

The constraints of SF-ESP are defined as follows:

(1) Capacity constraints for electricity generation:

$$[EC_{jk} + \sum_{m=1}^{3}\sum_{p=1}^{k} V_{jmp} \cdot Y_{jmp}] \cdot YH \cdot CF_j \geq X_{jk}, \quad \forall j,k \quad (4.2g)$$

(2) Electricity demand constraints:

$$\Pr\left[\sum_{j=1}^{5} X_{jk} \geq D_k(t)\right] \geq 1 - p_{k,D}, \ \forall k \quad (4.2h)$$

(3) CCS technology constraints:

$$X_{1k} \geq YH \cdot CC \cdot CFC, \quad \forall k \quad (4.2i)$$

(4) Capacity expansion constraints:

$$\sum_{k=1}^{4}\sum_{m=1}^{3} V_{2mk} \cdot Y_{2mk} \leq VC_2 \quad (4.2j)$$

$$\Pr\left[\sum_{k=1}^{4}\sum_{m=1}^{3}V_{jmk}\cdot Y_{jmk}\leq VC_j(t)\right]\geq 1-p_{j,VC},\ \ j=4,\ 5 \qquad (4.2k)$$

(5) Renewable generation capacity constraints:

$$\sum_{j=3}^{5}EC_{jk}+\sum_{j=3}^{5}\sum_{p=1}^{k}\sum_{m=1}^{3}V_{jmp}\cdot Y_{jmp}\geq(\sum_{j=1}^{5}EC_{jk}+\sum_{j=1}^{5}\sum_{p=1}^{k}\sum_{m=1}^{3}V_{jmp}\cdot Y_{jmp})\cdot RQ_k,\ \forall k \qquad (4.2l)$$

(6) Expansion option contraints:

$$\sum_{m=1}^{3}Y_{jmk}\leq 1,\ \forall j,k \qquad (4.2m)$$

$$\sum_{m=1}^{3}Y_{jmk}=0,\ j=1\text{ or }3,\ \forall k \qquad (4.2n)$$

$$Y_{jmk}=0\text{ or }1,\ \forall j,m,k \qquad (4.2o)$$

(7) Non-negativity constraints:

$$X_{jk}\geq 0,\ \forall j,k \qquad (4.2p)$$

where:

EC_{jk} = existing capacity of power-generation technology *j* in period *k* (MW);

YH = hours during a year (i.e. 24 × 365) (hours);

CF_j = capacity factor for technology *j* (%);

$D_k(t)$ = total electricity demand in period *k* (MWh);

CC = power generation capacity for Boundary dam unit 3 with CCS technology (MW);

CFC = capacity factor for CCS-based power generation technology (%);

VC_2 = allowable capacity increase for natural gas-fired power-generation technology (MW);

$VC_j(t)$ = allowable capacity increase for solar energy (j = 4) and wind power (j = 5) technologies (MW);

$p_{k,D}$ = constraint-violation probability for electricity demand constraints;

$p_{j,VC}$ = constraint-violation probability for availability constraints of solar energy (j = 4) and wind power (j = 5);

RQ_k = renewable capacity requirement (%).

Model Scenario 1: Basic-regulation scenario

Since the system cost became the only concern under this cost-effective scenario, which does not have renewable generation capacity constraints, the following linear cost minimization objective (4.2q) will replace the efficiency maximization objective (4.2 f) in Model (1):

$$\text{Min } f = \sum_{j=1,2,5} \sum_{k=1}^{4} 5 \cdot P_{jk} \cdot X_{jk} + \sum_{j=1}^{5} \sum_{k=1}^{4} 5 \cdot \mathrm{C}_{jk} \cdot X_{jk} + \sum_{j=2,4,5} \sum_{m=1}^{3} \sum_{k=1}^{4} E_{jmk} \cdot V_{jmk} \cdot Y_{jmk}$$

(4.2q)

This leads to a chance-constrained linear programming model and can be solved through the method presented in Zhu and Huang. 2013.

Model Scenario 2: Optimal-cost scenario

The model objective will be the same as that in Scenario 1 (4.2q), but with renewable generation capacity constraints (4.2l).

This also leads to a chance-constrained linear programming model and can be solved through the method presented in Zhu and Huang. 2013.

Model scenario 3: Optimal-efficiency scenario

The developed SF-ESP model has been applied in this scenario to find the best system efficiency between total system costs and GHG emissions reduction obligation. The system efficiency defined as the tonnes of GHG emissions reduction per unit of cost during the designed four time period, which is 20-years planning horizon. The results were obtained by solving both stochastic linear programming (SLP) and SF-ESP models, which based on the developed solution methods by Zhu et al. (2014).

4.3 Results Analysis and Discussion

Through modeling results, the analysis found that the most cost-competitive option is to replace affected coal-fired generation units with high efficiency natural gas-fired plants. However, without knowing the federal performance standards for natural gas-fired electricity, there will be a certain degree of risk to switching all coal-fired units to gas-fired units. The study found wind power is the best positioned to play a significant role in assisting Saskatchewan to reach the GHG emissions reduction target.

4.3.1 Results under scenario 1: Basic Regulation Scenario

The results of electricity generation by different technology options and capacity expansion options under Basic Regulation Scenario are presented in Tables 4.7 and 4.8. As shown in Table 4.7, the net coal-fired generation would decline in every period under all three p_i levels, due to planned retirement of the affected coal-fired generation units under the federal performance standards. However, coal-fired generation units will still operate at the maximum allowable generation under the federal performance standards, which is because coal is the most cost-effective fuel source compared with others. The power generation patterns and capacity expansion option are different under each p_i level. For instance, when $p_i = 0.01$, the electricity generation for coal-fired, natural gas-fired, hydropower, solar and wind power options in period 1 ($k = 1$) would respectively be 10,564, 11,330,295, 4,087,066, 3,504 and 320,224 MWh, and there is no capacity expansion for natural gas-fired, solar and wind power generation options under Period 1. Similarly, the electricity system planning for the remaining time periods under each p_i level can be determined. As shown in table 4.8, new solar power net capacity will only have limited expansion in Period 1 when $p_i = 0.1$, since almost all the baseload demand will be filled by natural gas-fired generation, and most of the intermediate demand will be filled by natural gas-fired and wind power generation. As shown in Figure 4.2, natural gas-fired will lead the expansion generation for all four periods but renewable sources will have limited growth. The system cost is the only concern under this scenario, therefore wind power will not be generated in periods 1, 2 and 3 are due to the demand side will be filled by natural gas-fired facilities. However, wind power will be used as intermittent and backup sources for other types of plants.

The major obstacle for this basic regulation scenario is that the federal government does not have natural gas-fired performance standards in place now. Without knowing the federal performance standards for natural gas-fired electricity, there is a degree of risk to switch all coal-fired units to natural gas-fired units. Natural gas prices have been maintained at a relatively low level for years, but potential rising natural gas prices in future may not make natural gas-fired technology as cost-effective as the results obtained in this case study.

Table 4.7 Electricity Generation Results from the Basic Regulation Scenario

Power Generation, X_{jk} (MWh)	Period	p_i = 0.01	p_i = 0.05	p_i = 0.1
Coal (j = 1)	k = 1	10,564,385	10,564,385	10,564,385
	k = 2	9,322,392	9,322,392	9,322,392
	k = 3	6,320,165	6,320,165	6,320,165
	k = 4	2,874,156	2,874,156	2,874,156
Natural gas (j = 2)	k = 1	11,304,015	11,073,841	10,910,860
	k = 2	14,446,292	14,166,675	13,991,347
	k = 3	20,007,554	19,702,681	19,513,892
	k = 4	25,923,512	21,731,852	21,731,852
Hydropower (j = 3)	k = 1	4,087,066	4,087,066	4,087,066
	k = 2	4,560,106	4,560,106	4,560,106
	k = 3	4,560,106	4,560,106	4,560,106
	k = 4	4,560,106	4,560,106	4,560,106
Solar (j = 4)	k = 1	3,504	3,504	29,784
	k = 2	3,504	3,504	29,784
	k = 3	3,504	3,504	29,784
	k = 4	3,504	3,504	29,784
Wind (j = 5)	k = 1	-	-	-
	k = 2	-	-	-
	k = 3	-	-	-
	k = 4	320,224	4,179,474	3,976,006

Table 4.8 Capacity Expansion Options Results from the Basic Regulation Scenario

Power Generation, $V_{jmk} \times Y_{jmk}$(MW)	Period	$p_i = 0.01$	$p_i = 0.05$	$p_i = 0.1$
Natural gas (j = 2)	$k = 1$	0	0	0
	$k = 2$	550 (m = 2)	550 (m = 2)	550 (m = 2)
	$k = 3$	700 (m = 3)	700 (m = 3)	700 (m = 3)
	$k = 4$	700 (m = 3)	300 (m = 1)	300 (m = 1)
Solar (j = 4)	$k = 1$	0	0	15 (m = 3)
	$k = 2$	0	0	0
	$k = 3$	0	0	0
	$k = 4$	0	0	0
Wind (j = 5)	$k = 1$	0	350 (m = 3)	350 (m = 3)
	$k = 2$	0	350 (m = 3)	350 (m = 3)
	$k = 3$	0	260 (m = 2)	170 (m = 1)
	$k = 4$	0	170 (m = 1)	170 (m = 1)

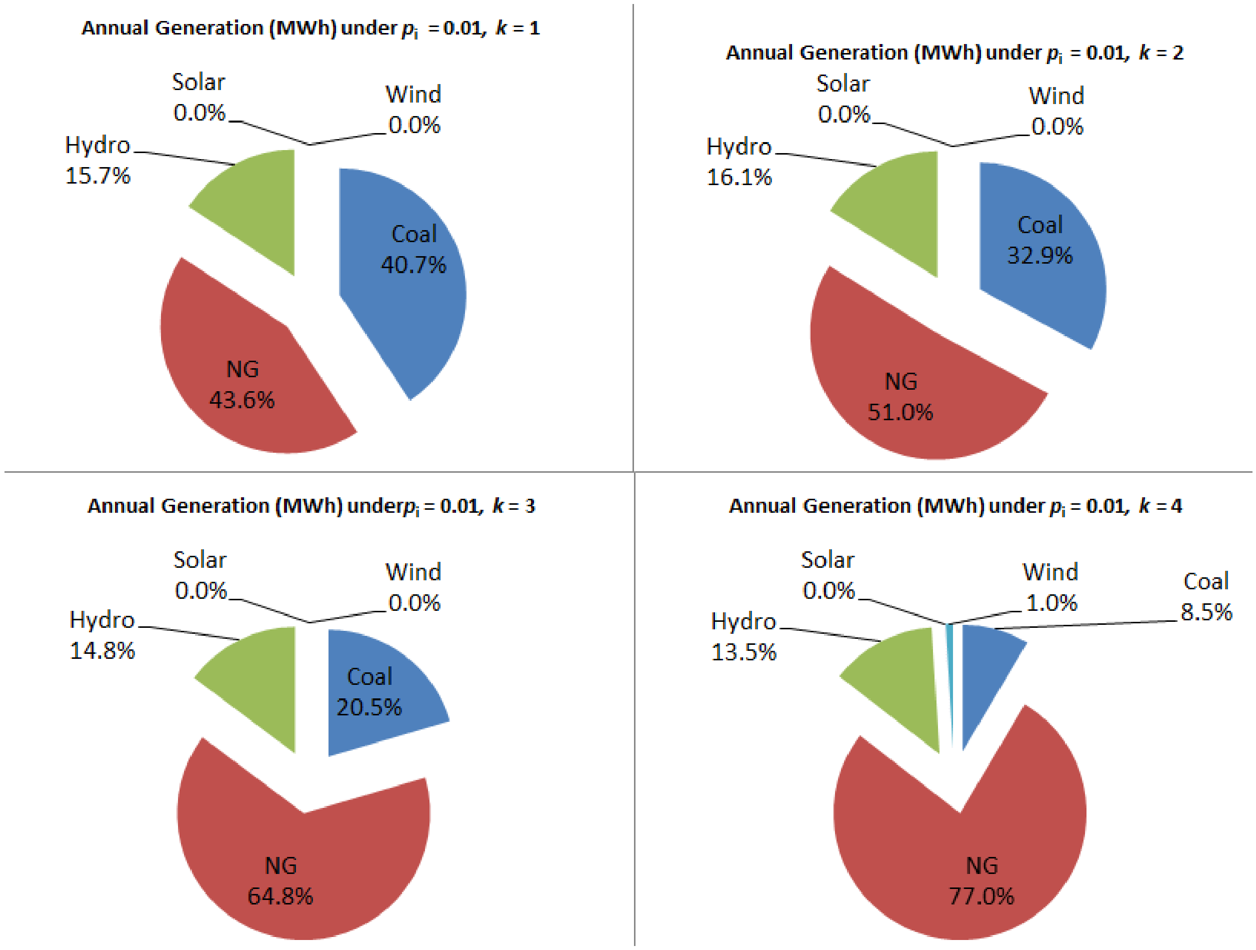

Figure 4.2 Comparisons of Fuel Sources Changes from the Basic Regulation Scenario

4.3.2 Results under scenario 2: Optimal-cost Scenario

The results of electricity generation by different technology options and capacity expansion options under the optimal-cost scenario are presented in Tables 4.9 and 4.10. As shown in Table 4.9, the net coal-fired generation would decline in every period under all three p_i levels due to the federal regulations for coal-fired generation units. However, these coal-fired units would still run at a maximum allowable emission level under the federal performance standards. Wind capacity would be installed for each period but would not start producing power until the last period. This is because other types of power plants could provide enough power for the demand side. The power generation patterns and capacity expansion option are different under each p_i level. For instance, when $p_i = 0.01$, the electricity generation for coal-fired, natural gas-fired, hydropower, solar and wind power options in period 1 ($k = 1$) would respectively be 10,564,385 11,304,015, 4,087,066, 29,784 and 0 MWh; the capacity expansion for natural gas-fired, solar and wind power options in period 1 would respectively be 350, 15 and 350 MW. The Figure 4.3 shows that natural gas-fired generation would grow rapidly under each study period, but renewable sources would have slight growth as well. Wind power generation would have significant growth in the last study period in comparison with basic regulation scenario. Similarly, the electricity system planning for the rest time periods under each p_i level can be interpreted.

The natural gas-fired plant is still the most attractive option under this scenario because of its cost efficiency. At the same time, as the primary baseload and intermittent sources cover the demand side, both generation and capacity expansion of natural gas-fired facilities would be continually increased by modest amounts in each period at all p_i levels.

Table 4.9 Electricity Generation Results from the Optimal-cost Scenario

Power Generation, X_{jk} (MWh)	Period	p_i = 0.01	p_i = 0.05	p_i = 0.1
Coal (j = 1)	*k* = 1	10,564,385	10,564,385	10,564,385
	k = 2	9,322,392	9,322,392	9,322,392
	k = 3	6,320,165	6,320,165	6,320,165
	k = 4	2,874,156	2,874,156	2,874,156
Natural gas (j = 2)	*k* = 1	11,304,015	11,073,841	10,910,860
	k = 2	14,393,732	14,166,675	13,965,067
	k = 3	19,951,490	19,702,681	19,461,332
	k = 4	22,208,177	22,208,177	22,208,177
Hydropower (j = 3)	*k* = 1	4,087,066	4,087,066	4,087,066
	k = 2	4,560,106	4,560,106	4,560,106
	k = 3	4,560,106	4,560,106	4,560,106
	k = 4	4,560,106	4,560,106	4,560,106
Solar (j = 4)	*k* = 1	29,784	3,504	29,784
	k = 2	56,064	3,504	56,064
	k = 3	59,568	3,504	82,344
	k = 4	63,072	3,504	108,624
Wind (j = 5)	*k* = 1	-	-	-
	k = 2	-	-	-
	k = 3	-	-	-
	k = 4	3,975,991	3,703,149	3,420,841

Table 4.10 Capacity Expansion Options Results from the Optimal-cost Scenario

Power Generation, $V_{jmk} \times Y_{jmk}$ (MW)	Period	p_i = 0.01	p_i = 0.05	p_i = 0.1
Natural gas (j = 2)	k = 1	350 (m = 3)	350 (m = 3)	150 (m = 1)
	k = 2	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 3	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 4	275 (m = 2)	275 (m = 2)	350 (m = 3)
Solar (j = 4)	k = 1	15 (m = 3)	0	15 (m = 3)
	k = 2	15 (m = 3)	0	15 (m = 3)
	k = 3	2 (m = 1)	0	15 (m = 3)
	k = 4	2 (m = 1)	0	15 (m = 3)
Wind (j = 5)	k = 1	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 2	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 3	170 (m = 1)	170 (m = 1)	260 (m = 2)
	k = 4	170 (m = 1)	170 (m = 1)	0

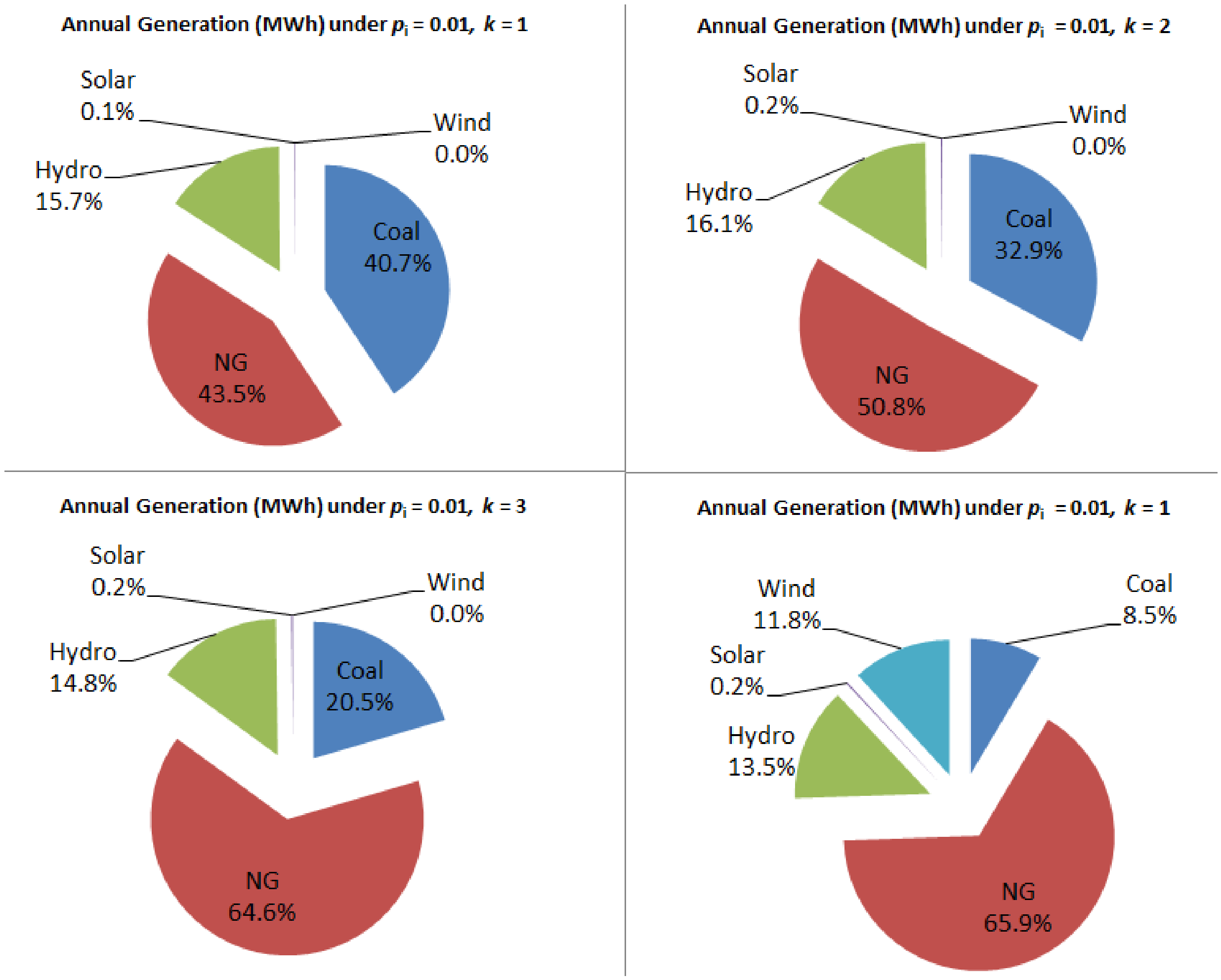

Figure 4.3 Comparison of Types of Fuel Sources from the Optimal-cost Scenario

4.3.3 Results under scenario 3: Optimal-efficiency Scenario

This scenario is designed to achieve the best system efficiency for power generation between system cost investments and environmental outcomes. The results of electricity generation by different technology options and capacity expansion options under the optimal-efficiency scenario are presented in Tables 4.11 and 4.12. As shown in Table 4.11, the net coal-fired generation would operate at the minimum level at every period under all three p_i levels, which is beyond the federal performance standards. Natural gas-fired and wind power generation would lead to additional electricity generation for each period. The power generation patterns and capacity expansion option are different under each p_i level. For instance, when $p_i = 0.01$, the electricity generation for coal-fired, natural gas-fired, hydropower, solar and wind power options in period 1 ($k = 1$) would respectively be 5,290,187, 14,777,507, 4,087,066, 29,784 and 1,800,706 MWh; the capacity expansion for natural gas-fired, solar and wind power options in period 1 ($k = 1$) would respectively be 350, 275, 15 and 350 MW. As shown in figure 4.7, renewable sources would have significant growth under each study period. Wind power generation would be the primary renewable sources to fill the generation demand side. Similarly, the electricity system planning for the rest time periods under each p_i level can be interpreted.

Although natural gas-fired generation would still be a very attractive option under this scenario because of its low cost, the growing wind power would become more important for the interpreted demand side. At the same time, solar power would be recognized as backup plants especially when demand slightly increases.

Table 4.11 Electricity Generation Results from Optimal-efficiency Scenario

Power Generation, X_{jk} (MWh)	Period	p_i = 0.01	p_i = 0.05	p_i = 0.1
Coal (j = 1)	*k* = 1	5,290,187	5,033,733	4,897,033
	k = 2	3,366,732	3,087,114	2,938,067
	k = 3	2,128,307	1,823,434	1,660,924
	k = 4	1,999,210	1,657,163	1,183,012
Natural gas (j = 2)	*k* = 1	14,777,507	14,777,507	14,777,507
	k = 2	17,444,927	17,444,927	17,444,927
	k = 3	20,112,347	20,112,347	20,112,347
	k = 4	22,208,177	22,208,177	22,208,177
Hydropower (j = 3)	*k* = 1	4,087,066	4,087,066	4,087,066
	k = 2	4,560,106	4,560,106	4,560,106
	k = 3	4,560,106	4,560,106	4,560,106
	k = 4	4,560,106	4,560,106	4,560,106
Solar (j = 4)	*k* = 1	29,784	29,784	29,784
	k = 2	56,064	56,064	56,064
	k = 3	82,344	82,344	82,344
	k = 4	85,848	95,484	108,624
Wind (j = 5)	*k* = 1	1,800,706	1,800,706	1,800,706
	k = 2	2,904,466	2,904,466	2,904,466
	k = 3	4,008,226	4,008,226	4,008,226
	k = 4	4,828,162	4,828,162	5,111,986

Table 4.12 Capacity Expansion Options Results from Optimal-efficiency Scenario

Power Generation, $V_{jmk} \times Y_{jmk}$ (MW)	Period	p_i = 0.01	p_i = 0.05	p_i = 0.1
Natural gas (j = 2)	k = 1	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 2	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 3	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 4	275 (m = 2)	275 (m = 2)	275 (m = 2)
Solar (j = 4)	k = 1	15 (m = 3)	15 (m = 3)	15 (m = 3)
	k = 2	15 (m = 3)	15 (m = 3)	15 (m = 3)
	k = 3	15 (m = 3)	15 (m = 3)	15 (m = 3)
	k = 4	2 (m = 1)	7.5 (m = 2)	15 (m = 3)
Wind (j = 5)	k = 1	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 2	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 3	350 (m = 3)	350 (m = 3)	350 (m = 3)
	k = 4	260 (m = 2)	260 (m = 2)	350 (m = 3)

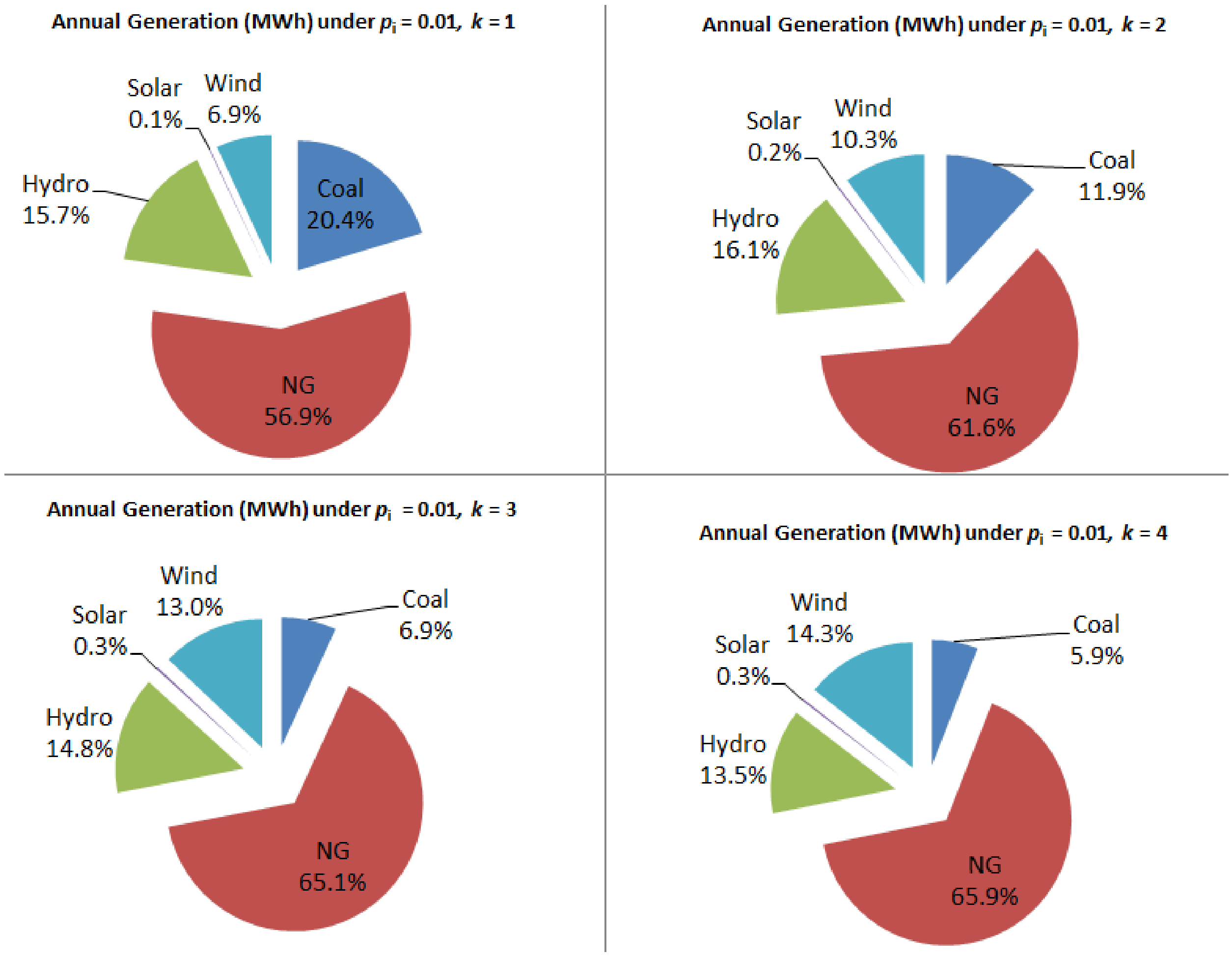

Figure 4.4 Comparison of Fuel Sources from the Optimal-efficiency Scenario

4.4 Results Comparison of Three Scenarios

Saskatchewan may have many options for its electrical system planning to feed the growing electricity demand in the future. Based on SaskPower's projections, the provincial net generating capacity will be increased to 7000 MW by 2030, which means the total net generating capacity will be increased more than 60% over the level in year 2015. The reliable and balanced power systems have to include baseload, baseload/peaking, peaking, intermediate and intermittent types of electricity generation. Given the diverse options of power sources, decision makers have to decide on the more reliable energy sources for day-to-day or short-time demand, while choosing other less reliable but more energy-efficient and environmental-friendly types as backup plans that supply power when consumers need more. The results of electricity generation, capacity expansion, and GHG emissions reduction from the three scenarios have been compared and discussed under this section.

(1) Coal-fired capacity changes

Figure 4.5 compares the results of coal-fired generation capacity corresponding to the basic regulation, optimal-cost and optimal-efficiency scenarios under $p_i = 0.01$, $p_i = 0.05$ and $p_i = 0.10$. Both basic regulation and optimal-cost scenarios indicate that coal-fired generation capacity will be reduced to match the federal coal-fired electricity standards at all three p_i levels. On the contrary, the optimal-efficiency scenario indicates that coal-fired generation capacity can be reduced beyond the federal performance standards requirements at an acceptable cost level.

(2) Over all system capacity changes of different power generation technologies in the end of the study period

Figures 4.6, 4.7 and 4.8 compare technology capacities under different p_i levels in the mixed power generation patterns from the three scenarios at Period 4, the end of the planning horizon (year 2035). In contrast, coal-fired generation capacity will account for 7% of total net capacity under the basic regulation and optimal-cost scenarios respectively. However, coal-fired generation capacity will only account for 4% of the total net capacity under the optimal-efficiency scenario. All three scenarios show hydropower will reach the maximum capacity for every period as hydropower is the most cost-competitive renewable energy source, as a result of the 20-years deal to buy electricity from Manitoba Hydro. Wind power will be the principal renewable fuel source under all p_i levels of all three scenarios, except for optimal-cost scenario under $p_i = 0.01$. However, natural gas will lead the primary fuel source under all three scenarios.

The optimal-efficiency scenario shows the renewable capacity expansion will achieve approximately 45% of the total net generating capacity under $p_i = 0.01$ and $p_i = 0.05$ at the end of the planning horizon, and 46% of the total net generating capacity under $p_i = 0.10$ at the last period $k = 4$. This modelling result is reasonable and matches the SaskPower's target that up to 50% of its generation capacity will be from renewable sources by 2030.

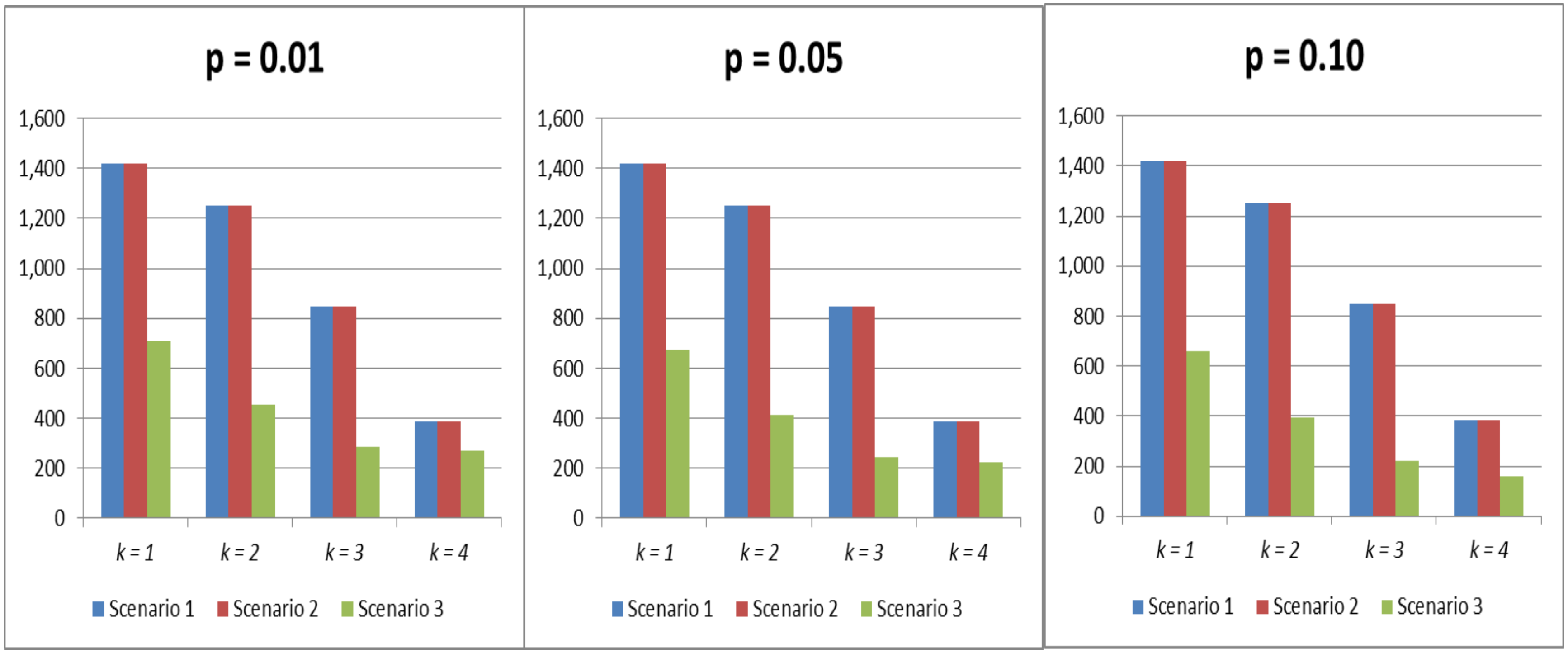

Figure 4.5 Comparison of Coal-fired Capacity (MW) under the Three Scenarios

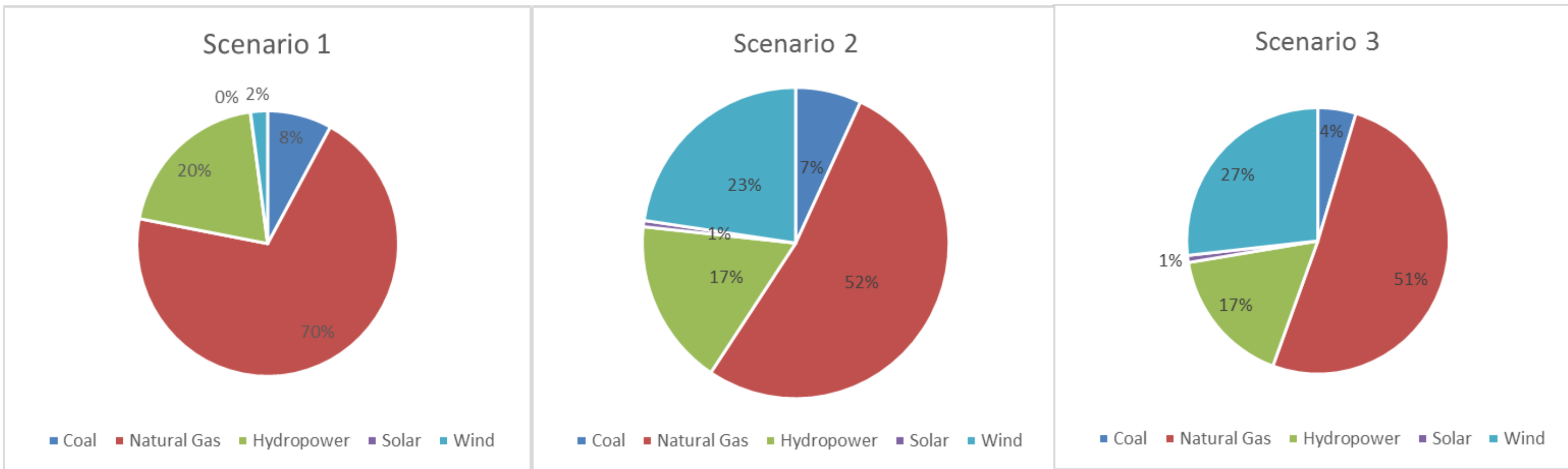

Figure 4.6 Comparison of Capacities Changes under Three Scenarios at k = 4, p_i = 0.01

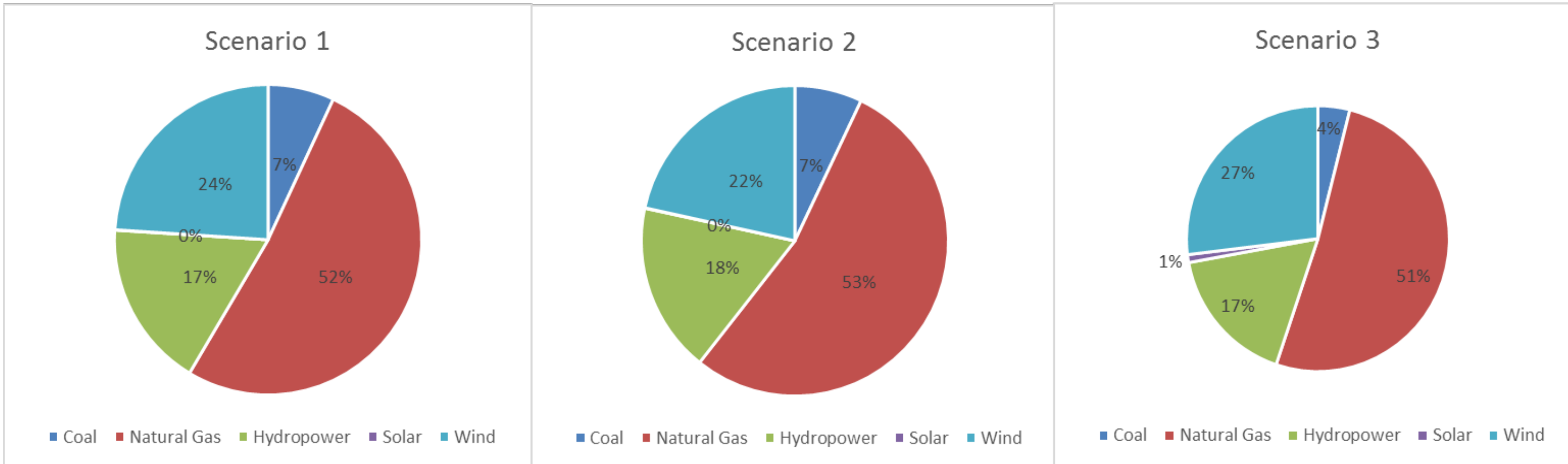

Figure 4.7 Comparison of Capacities Changes under Three Scenarios at k = 4, p_i = 0.05

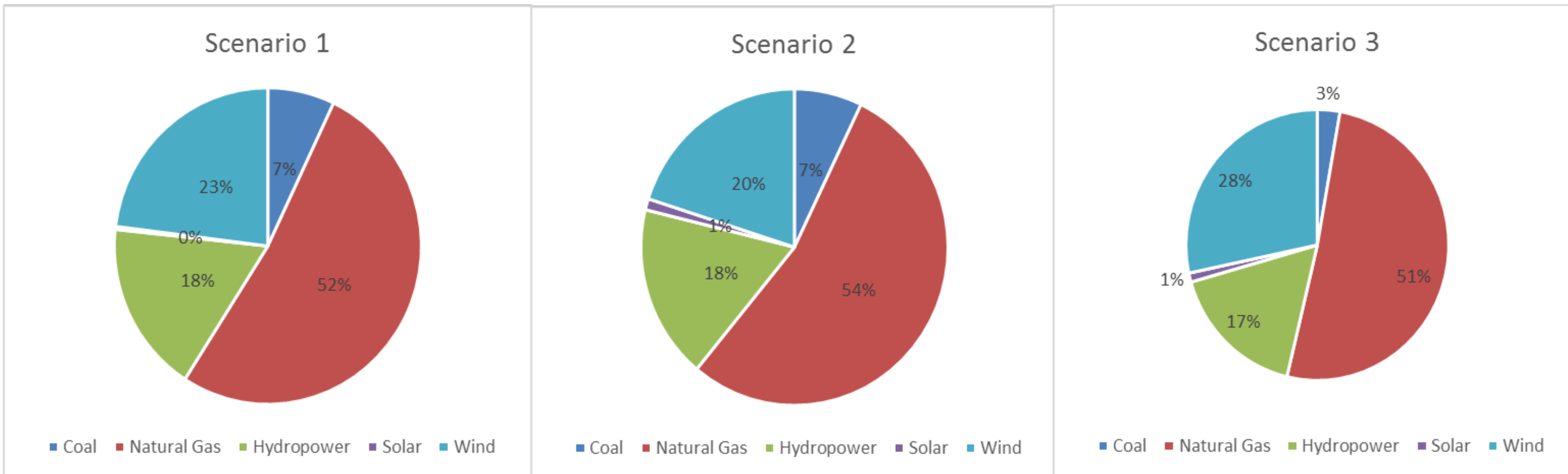

Figure 4.8 Comparison of Capacities Changes under Three Scenarios at k = 4, p_i = 0.10

(3) GHG Emissions Reduction

Figure 4.9 shows fleet-wide GHG emissions trends within the four study periods under the three scenarios at different p_i levels. When p_i = 0.01, the basic-regulation and optimal-cost scenarios have slightly different GHG emissions trends during the first three time periods, but optimal-cost scenario has a better environment performance at the last time period. By comparing all three scenarios, Optimal-cost Scenario leads the best environment performance for all time periods. When p_i changes to p_i = 0.05 and p_i = 0.10, the basic regulation scenario and optimal-cost scenario have similar GHG emissions trends during all four study periods. In contrast, the optimal-efficiency scenario still leads to a relatively higher environment performance than the other two models for all times as well.

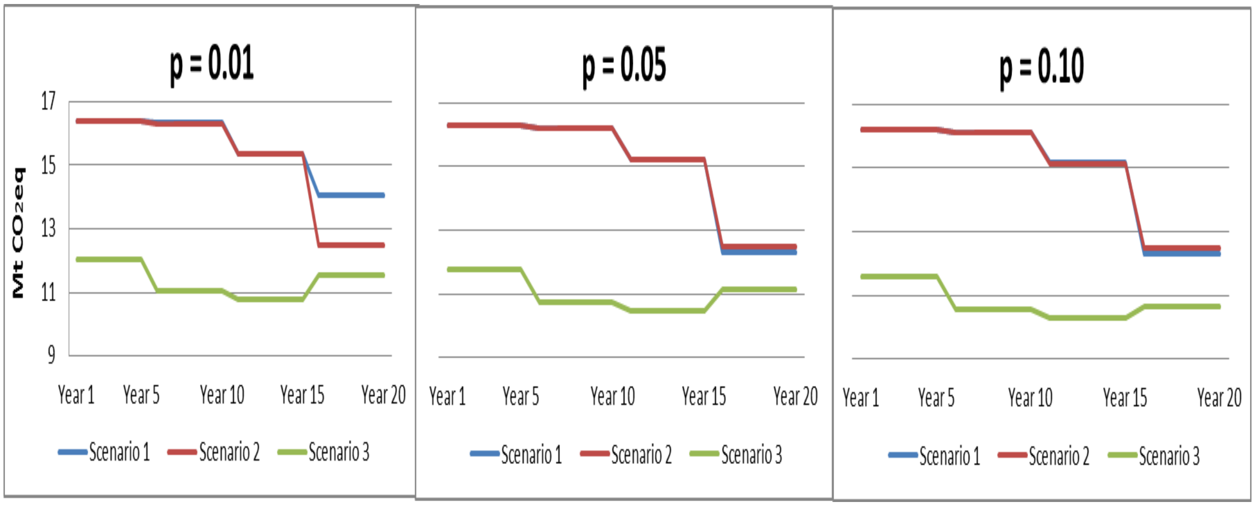

Figure 4.9 Comparison of Fleet-Wide GHG Emissions under Scenario 1, 2 and 3 Within Overall Study Period: *k* = 1 (year 1-5); *k* = 2(year 6-10); *k* = 3 (year 11-15); and *k* = 4 (year 16-20).

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

In this research, a Stochastic Fractional Electricity System Planning (SF-ESP) model has been developed for the planning of future electricity system under Canada *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations* in Saskatchewan. In order to comply with the federal performance standards and meet continued demand for future generation, this research developed a SF-ESP model to address capacity expansion, GHG emissions reduction issues under uncertainty from a long-term perspective, where techniques of chance-constrained programming (CCP), mixed-integer linear programming (MILP), and linear fraction programming (LFP) are integrated into a general framework.

The proposed SF-ESP model can provide comprehensive analysis of both economic and environmental implications under stochastic uncertainty, and help decision makers balance cost-competitive and GHG emissions mitigation targets under different climate change policy scenarios. In Saskatchewan, the major GHG emitters in electricity generation sector are coal-fired and natural gas-fired power plants. Accordingly, the proportion of natural gas-fired and renewable generation expansion in future will be the primary key factor to drive the provincial GHG emissions trend in electricity sector. Dual diligence and careful strategic planning are paramount for Saskatchewan decision makers to seek minimum environmental impacts associated with power production, and to develop potential regulations on other types of fuel sources in future.

5.2 Research achievements

This research is the first attempt to build an electricity system planning model in Saskatchewan to provide options for decision makers to solve the immediate issue of federal regulatory oversight of Saskatchewan coal-fired power plants beginning July 1, 2015. Reasonable capacity expansion options for electrical system in Saskatchewan are obtained through the SF-ESP model from the present to next 20 years. This study has also developed three scenarios for comparing comprehensive impacts under different climate change policies. Based on the case study results, decision makers can have a better understanding of the tradeoffs and relationships among multiple system components.

5.3 Recommendation for future research

(1) This research applied the stochastic fractional programming approach for analyzing conflicting economic and environmental objectives under uncertainty. Given the inherent uncertainty in real-world optimization problems, other uncertainty analysis techniques could also be incorporated to reflect various forms of uncertainties like fuzzy sets and interval parameters.

(2) This study considered natural gas-fired, hydropower, solar and wind power as the capacity expansion options for Saskatchewan. Nuclear power was not included in this case study as it has not been announced as an option for the Saskatchewan. However, small nuclear reactors may be more applicable, reliable and economical in small communities with current technologies. Future energy system studies in Saskatchewan could incorporate small nuclear reactors as an alternative option for capacity expansion.

(3) This research analyzed the power system optimization options under the *Reduction of Carbon Dioxide Emission from Coal-fired Generation of Electricity Regulations*. The

environment outcome was focused on carbon dioxide, because it is the only regulated GHG emission gas under the regulations. The ECCC GHG Emissions Reporting Program indicated that Saskatchewan existing power stations also emit methane and nitrous oxide. Future studies could include methane and nitrous oxide emissions in GHG emissions analysis so that the total carbon dioxide equivalent (CO_{2e}) reductions can be also reflected.

REFERENCE

Balat, M. (2007). Influence of coal as an energy source on environmental pollution. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *29*(7), 581-589.

Bataille, C., Melton, N., & Jaccard, M. (2015). Policy uncertainty and diffusion of carbon capture and storage in an optimal region. *Climate Policy*, *15*(5), 565-582.

Brige, J.R., and Louveaux, F. (1997). *Introduction to Stochastic Programming Springer, New Yrok.*

Burt, E., Orris, P., & Buchanan, S. (2013). Scientific evidence of health effects from coal use in energy generation. *Chicago and Washington: School of Public Health, University of Illinois and Health Care Without Harm*.

De Carvalho, A. L., Antunes, C. H., Freire, F., & Henriques, C. O. (2016). A multi-objective interactive approach to assess economic-energy-environment trade-offs in Brazil. *Renewable and Sustainable Energy Reviews*, *54*, 1429-1442.

Environment and Climate Change Canada (2012*). Part A: Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations,* 146, No.19.

Environment and Climate Change Canada (2016). *Canada National Inventory Report 1990-2014: Greenhouse Gas Sources and Sinks in Canada*.

Environment and Climate Change Canada. *GHG Emissions Quantification Guidance.* Available online: https://www.ec.gc.ca/gesghg/default.asp?lang=En&n=DDCA72D0-1(accessed on 16 May 2016).

European Union - *Emission Database for Global Atmospheric Research*: 'GHG time series 1990-2012 per capita emissions for world countries'. Sask data ex Environment Canada. Table A10-16 2015 National Inventory Report Part 3 (GHG data for 2012).

Government of Saskatchewan (2014). *Economic Review 2013 (Number Sixty-Seven) of Government of Saskatchewan*. Available online: http://www.stats.gov.sk.ca/stats/ER2013.pdf (accessed on 16 May 2016).

Hoffman, K. C., & Wood, D. O. (1976). Energy system modeling and forecasting. *Annual review of energy*, *1*(1), 423-453.

Hofman, K., & Li, X. (2009). Canada's energy perspectives and policies for sustainable development. *Applied Energy*, *86*(4), 407-415.

Kamjoo, A., Maheri, A., Dizqah, A. M., & Putrus, G. A. (2016). Multi-objective design under uncertainties of hybrid renewable energy system using NSGA-II and chance constrained programming. *International Journal of Electrical Power & Energy Systems*, 74, 187-194.

Kim, S., & Dale, B. (2005). Life cycle inventory information of the United States electricity system (11/17 pp). *The International Journal of Life Cycle Assessment*, *10*(4), 294-304.

Li, Y. P., Huang, G. H., Nie, S. L., & Qin, X. S. (2007). ITCLP: An inexact two-stage chance-constrained program for planning waste management systems. *Resources, Conservation and Recycling*, *49*(3), 284-307.

Liming, H., Haque, E., & Barg, S. (2008). Public policy discourse, planning and measures toward sustainable energy strategies in Canada. *Renewable and Sustainable Energy Reviews*, *12*(1), 91-115.

Liu, Y., Cai, Y. P., Yang, Z. F., Tan, Q., & Lin, X. (2016). Identification of optimal recourse strategies for power generation under a government-guided coal-pricing mechanism in north China. *International Journal of Electrical Power & Energy Systems*, 79, 210-227.

Mundaca, L., Neij, L., Worrell, E., & McNeil, M. (2010). Evaluating energy efficiency policies with energy-economy models. *Annual review of environment and resources*, *35*, 305-344.

Olson, D. L., & Swenseth, S. R. (1987). A linear approximation for chance-constrained programming. *Journal of the Operational Research Society, 38* (3), 261-267.

Raghuvanshi, S. P., Chandra, A., & Raghav, A. K. (2006). Carbon dioxide emissions from coal based power generation in India. *Energy Conversion and Management*, *47*(4), 427-441.

SaskPower (2012). *Customer Guide to the SaskPower system*. Available online: http://www.saskpower.com/wp-content/uploads/saskpower_system_customer_guide.pdf (accessed on 16 May 2016).

SaskPower (2015). *Develop wind, solar and geothermal power to meet up to 50% renewable target*, *2015*. Available online: http://www.saskpower.com/about-us/media-information/saskpower-targets-up-to-50-renewable-power-by-2030/ (accessed on 16 May 2016).

SaskPower (2016). *2014 Annual Report*.

Skantze, P., Ilic, M., & Chapman, J. (2000). Stochastic modeling of electric power prices in a multi-market environment. In *Power Engineering Society Winter Meeting, 2000. IEEE* 2, 1109-1114.

Statistics Canada (2016). *Report on Energy Supply and Demand in Canada (RESDC).*

Suzuki, S., & Nijkamp, P. (2016). An evaluation of energy-environment-economic efficiency for EU, APEC and ASEAN countries: Design of a Target-Oriented DFM model with fixed factors in Data Envelopment Analysis. *Energy Policy*, *88*, 100-112.

U.S. Environmental Protection Agency (2009). *EPA's Endangerment Finding: Health Effects.*

U.S. Environmental Protection Agency (2015). *U.S. Energy Information Administration, Annual Energy Outlook 2015,* DOE/EIA-0383.

U.S. Environmental Protection Agency (2009). *Technical Support Document for Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act.*

Wallace, S. W., & Fleten, S. E. (2003). Stochastic programming models in energy. *Handbooks in operations research and management science*, *10*, 637-677.

Wang, Q., Guan, Y., & Wang, J. (2012). A chance-constrained two-stage stochastic program for unit commitment with uncertain wind power output. Power Systems, *IEEE Transactions on*, *27*(1), 206-215.

Worrell, E., Ramesohl, S., & Boyd, G. (2004). Advances in energy forecasting models based on engineering economics*. *Annu. Rev. Environ. Resour.*, *29*, 345-381.

Zhu, H., & Huang, G. H. (2011). SLFP: a stochastic linear fractional programming approach for sustainable waste management. *Waste Management*, *31*(12), 2612-2619.

Zhu, H., & Huang, G. H. (2013). Dynamic stochastic fractional programming for sustainable management of electric power systems. *International Journal of Electrical Power & Energy Systems*, *53*, 553-563.

Zhu, H., Huang, W. W., & Huang, G. H. (2014). Planning of regional energy systems: An inexact mixed-integer fractional programming model. *Applied Energy*, *113*, 500-514.