Management of Canada’s energy transition and associated risks through optimized CGE approach

The model

1. Introduction

In energy system planning and management, various interconnected components must be considered, including social, environmental, economic, technical, legislative and political issues. All of these issues present different spatial, temporal, and functional features, which make the modeling process more difficult and complex. Therefore, system optimization methods need to be introduced to comprehensively reflect influences of various factors, analyze relationships among multiple components, and thus provide maximized economic, social, and environmental benefits. The energy system optimization modeling is effective for analyzing trade-offs between environmental and social-economic objectives and providing scientific supports for energy related policy-making. In detail, It could help (a) obtain better understanding of current and future energy markets (e.g., supply, demand, and prices); (b) facilitate better planning of energy supply systems in short, medium, and long term; (c) ensure sustainable development of various kinds of resources; (d) understand potential impacts on environmental quality. Traditional deterministic optimization programming includes linear, integer, and dynamic methods. With the advantages of concise performance and easy operation, deterministic optimization programming has been widely applied in system planning and management. In most cases of energy systems, the optimization objectives is to minimize the costs and risks or maximize the benefits.

In addition, energy systems have close relationships with a variety of socio-economic activities. Previous energy systems planning generally focused on energy- and environment-related issues through various optimization methods, while effects from a number of socio-economic factors were simplified. Computable General Equilibrium (CGE) models are widely used to simulate the impacts of economic activity or policy to the entire socio-economic system. The economic data is used in CGE models to estimate the general and detailed responses caused by changes of policy, technology or other external factors. The basic economic units it analyzes are producers, consumers, governments and foreign economies. The data foundation in CGE model process is the social accounting matrix. Through CGE model, the complexity of the micro-macro interrelationships can be better performed. However, CGE model cannot reflect the specific response of industries and sectors. For example, industry may take clean energy technology to reduce emissions, which cannot be reflected in CGE model.

Developing optimized Computable General Equilibrium (CGE) models could facilitate the energy systems transition analysis and related risk management. By integrating the characteristics of these two modeling methods, the proposed methods can address the interaction of economy, environment, social factors and explore the impacts of different mechanisms in energy systems more effectively. In detail, energy system optimization model can represent energy system and guide future energy system developments. The optimization model captures different technology potentials, costs, and conversion efficiencies within a particular energy system. Therefore, these models can provide the detailed choices and operations in a given system with a given set of requirements. Because they focus on the analysis of specific energy technologies and related investment options, they can be called bottom-up models. Instead, a CGE model is often used to assess the development of the entire economy, which consistently represents the interactions between different economic sectors. The CGE model is a balancing tool designed to explain the behaviors of supply, demand, and relative prices across the economy with many markets. As a top-down economic tool, CGE model can simulate the energy prices and demand through an organic combination of actual macroeconomic data.

In summary, integration of CGE and optimization models represents an innovation for enhancing the socio-economic aspects of energy systems planning; the resulting CGE-based energy systems optimization method can be used for assessing the benefits of various energy policy scenarios to the whole socio-economic systems, and thus generating desired energy management plans that reflect trade-offs among various energy and socio-economic criteria.

2 Methodology

2.1 Optimization modeling of energy management systems

Energy system management modeling requires reasonable planning of the available sources to best satisfy the energy requirements. For example, in a typical regional energy system, several kinds of energy resource types can be developed in order to meet the overall energy demand. To ensure the effectiveness of energy production and utilization, system managers have to consider socio-economic status, environmental implications as well as some technical constraints to formulate most optimal energy development plans.

2.1.1 Deterministic modeling

In most cases of energy systems, optimization objectives focus either on maximizing the system benefits or minimizing the total system costs and risks. For conventional deterministic optimization programming, taking a “cost minimization” case as an example, the objective function of the model is to minimize the overall system cost, which is composed of several sections. Also, it is restrained by several constraints resulting from social, economic, environmental and some other aspects.

A typical energy model can be built as follows:

$$Min\ f = C_1 + C_2 + C_3 + \ldots + C_n \tag{1}$$

1. Costs for energy resources supply

$$C_1 = \sum_{i}^{I}\sum_{k}^{K} CS_{i,k} \times XS_{i,k} \tag{2}$$

2. Cost for electricity generation

$$C_2 = \sum_{j}^{J} \sum_{k}^{K} CE_{j,k} \times XE_{j,k} \tag{3}$$

3. Capital costs for capacity expansion

$$C_3 = \sum_{j}^{J} \sum_{m}^{M} \sum_{k}^{K} XC_{j,m,k} \times CC_{j,m,k} \times y_{j,m,k} \tag{4}$$

4. Costs for pollutants treatment

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Subject to:

(a) Mass balance of electricity

$$DME_{s,k} \leq AEL_{s,k} \ \forall s,k \tag{5}$$

$$\sum_{s}^{S} AEE_{s,k} \leq \sum_{j}^{J} XE_{j,k} \times R \ \forall k \tag{6}$$

(b) Mass balance of energy resources

$$DMR_{i,s,k} \leq ARL_{i,s,k} \ \forall i,s,k \tag{7}$$

$$ARL_{i,s,k} \leq XS_{i,s,k} \times R \ \forall i,s,k \tag{8}$$

(c) Emissions control constraint

$$\sum_{m}^{M} XE_{m,k} \times EF_{m,k} + \sum_{i}^{I} \sum_{s}^{S} ARL_{i,s,k} \times AEF_{i,s,k} \leq STD_k \ \forall k \tag{9}$$

(d) Capacity constraints

(e) Technology constraints

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Subscripts:

i: Primary energy resources (*i* = 1, 2, ..., I)

s: Energy end-user sectors (*s* = 1, 2, ..., S)

k: Planning period (*k* = 1, 2, ..., K)

j: Electrical generation technologies (*j* = 1, 2, ..., J)

m: Expansion options of Capacity (*m* = 1, 2, ..., M)

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Decision variables:

$XS_{i,k}$: Amount of resource *i* inputted during period *k* (GJ)

$XE_{j,k}$: Amount of electricity generated by technology *j* during period *k* (MWh)

$y_{j,m,k}$: Integer variable identifying capacity for technology *j* with capacity-expansion option *m* in period *k* will be installed or not;

$ARL_{i,s,k}$: Resource *i* allocated to end-user *s* during period *k* (GJ)

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Parameters:

$CS_{i,k}$: Cost of resource *i* during period *k* ($/GJ)

$CE_{j,k}$: Cost of power generation by technology *j* during period *k* ($/MWh)

$CC_{j,m,k}$: Cost of power capacity expansion for technology *j* with option *m* during period *k* ($/MW)

$DMR_{i,s,k}$: Amount of resource *i* demanded by end-user *s* during period *k* (GJ)

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2.1.2 Optimization modeling under uncertainty

Deterministic programming is effective at solving decision-making problems to a certain extent. However, energy system planning and management problems are associated with a variety of uncertainties caused by systematic measurement, parameter estimation, random characteristics of natural events and some other factors in real world cases. To generate practical and precise analysis results for decision making, various kinds of uncertainties need to be considered. Therefore, uncertainty analysis is necessary to be introduced into energy system modeling process to increase its feasibility. Four of the most widely used uncertain programming methods are described as follows:

- **Interval mathematical programming (ILP)**

Interval mathematical programming (ILP) is effective at addressing uncertain information with known upper and lower bounds but unknown distribution functions [1]. For instance, in an energy system, future energy purchase prices might have different values depending on different prediction models or scenarios, which can be expressed as an interval number with known upper and lower values.

For example, by introducing ILP into the modeling process, eq. (9) can be rewritten as:

$$\sum_{m}^{M} XE^{\pm}_{m,k} \times EF^{\pm}_{m,k} + \sum_{i}^{I}\sum_{s}^{S} ARL^{\pm}_{i,s,k} \times AEF^{\pm}_{i,s,k} \le STD^{\pm}_{k} \quad \forall k \tag{10}$$

- **Chance-constrained programming (CCP)**

Chance-constrained programming (CCP) can deal with uncertainties in right-hand-side (RHS) parameters when the probability distributions are known[2]. In CCP methods, a certain level of probability p_i ($p_i \in [0,1]$) is given to constraint *i*, indicating that the constraint should be satisfied with at least a probability of 1-p_i. In an energy system, for example, considering the random features caused by economic and social development, energy demands can be presented as probability distributions. Eq (5) can be converted as a typical CCP expression:

$$\Pr[DMR_{i,s,k} \le ARL_{i,s,k}(t)] \ge 1 - p_i \;\; \forall i,s,k \tag{11}$$

Where $t \in T$, $ARL_{i,s,k}(t)$ is a RHS parameter defined on a probability space *T*; the left-hand-side (LHS) parameter $DMR_{i,s,k}$ are deterministic.

- **Two-stage stochastic programming (TSP)**

Many problems in energy system planning procedures require that decisions be made periodically over time, which can often be represented by two-stage stochastic programming (TSP) models. In TSP, a decision is first made based on random future event and then, after the uncertain events have happened and their values are available, a corrective action is taken so as to minimize "penalties" resulted from any infeasibility [3]. When introducing TSP into the energy model, Eq (2) can be converted into:

$$C_2 = \sum_{j}^{J}\sum_{k}^{K} CE_{j,k} \times XE_{j,k} + \sum_{j}^{J}\sum_{k}^{K}\sum_{h}^{H} p_{kh} \times EQ_{j,k,h} \times (CE_{j,k} + CP_{j,k}) \tag{12}$$

Where *h* is the demand level of power load; p_{kh} is the probability of occurrence for power demand scenario *h* in period *k*; $CP_{j,k}$ is the penalty cost for power generated from technology *j* in period *k*; $EQ_{j,k,h}$ is the excess amount of electric generation for technology *j* in power demand scenario *h* during period *k*.

- **Fuzzy linear programming (FLP)**

In the real world, the majority of available information is inexact, and may only be presented as interval without knowledge of probability distribution function but with known membership function [4]. Therefore, fuzzy linear programming (FLP) could be adopted to tackle the uncertainties expressed as fuzzy membership functions. When introducing FLP into the energy model, Eq (9) can be rewritten as:

$$\sum_{m}^{M} XE_{m,k} \times EF_{m,k} + \sum_{i}^{I}\sum_{s}^{S} ARL_{i,s,k} \times AEF_{i,s,k} \le STD_k \;\; \forall k \tag{13}$$

Where $EF_{m,k}$, $AEF_{i,s,k}$ and STD_k are fuzzy coefficients and can be considered as triangular fuzzy sets. For example, $\tilde{STD}_k = \left(\underline{STD_k}, STD_{k0,}, \overline{STD_k}\right)$.

Typically, various kinds of uncertainties exist in energy systems in the forms of parameters and model structures. These complexities are further intensified due to the interactions of multiple uncertainty sources. By integrating different methods into one framework, multiple uncertainties can be addressed effectively.

2.1.3 Case study

2.1.3.1 British Columbia

An integrated algorithm based on chance-constrained two-stage fractional regional energy model (CTFO-REM) is proposed to optimize energy management schemes under multi-objective planning requirements in the province of British Columbia, Canada [5]. Through constructing a linear fractional programming (LFP) framework as a base, and integrating two-stage stochastic programming (TSP), mixed-integer linear programming (MILP), and chance-constrained programming (CCP) methods together, CTFO can effectively deal with uncertainties described as probability distributions in the objectives and constraints.

The proposed CTFO-REM model has the advantages in (1) tackling multiobjective and capacity-expansion issues, (2) providing multi-staged planning details, (3) giving consideration to randomness existing in the constraints and objective, and (4) revealing the internal relationship among economic cost, system reliability, and policy scenarios. In addition, methods of the CTFO-REM model can also be extended to other practical issues such as solid waste optimization, water resource allocation, and the management of air quality.

For example, the multi-objective conflicting can be quantitatively solved by the fractional framework in equation (14)

$$Max\ f = \frac{\sum_{j=5}^{10} XP_{jt} + \sum_{k=3}^{3} XH_{kt}}{f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7} \tag{14}$$

Where XP_{jt} represent the renewable power generation for j during period t; XH_{kt} represent the renewable heat generation for k during period t; $f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7$ represent the overall system cost in the objective function. Specifically, f_2 illustrates the application of two-stage algorithm for the cost of power generation, which consists of two parts: target generation cost, and recoursed power generation cost.

2.1.3.2 Alberta

To address the Alberta’s integrated energy-environment systems (IEES) planning problem, an interval fuzzy two-hand-side joint probabilistic chance-constrained programming model (IFTCP-IEES) is developed [6]. The objective of this model is to minimize the net system cost, which is relevant to energy supply, energy processing, energy demand, conversion of electricity, resource supply options, capacity expansion options, and greenhouse gas emission (GHG) mitigation. The planning horizon is from 2003 to 2027, which includes five periods with 5 years in each period.

Typical advantages of the IFTCP-IEES are: (1) reflecting system dynamics associated with capacity expansions using interval linear programming and showing random distributions by chance-constrained programming; (2) addressing ambiguous system information related to GHG reductions (such as offset credit availability) by integrating fuzzy programming, for example, the constrains to obtain the maximum value of λ are the applications; (3) showing the impacts of varying climatic conditions and communicating them into multiple components of the IEES; (4) reflecting the reliability of meeting constraints upon the entire system.

For example, the advantage (1) is represented in equation (15):

$$Pr\left\{\left(CRD_{t,c}^{\text{北}} + \sum_{t} YCB_{t,c,o} \text{鬓} CEB_{t,c,o}\right) \; CF_{t,c}^{?}(w) \geq XE_{t,c}^{\pm}\right\} \geq 1 - p_{c}, \forall\ t,c \qquad (15)$$

where

$CRD_{t,c}^{\pm}$: residual capacity of power technology c in time period t (GWe);

$YCB_{t,c,o}$: capacity expansion option o for power generation technology c in time period t;

$CEB_{t,c,o}^{\pm}$: scale capacity of expansion option o for power generation technology c in time period t (GWe);

$CF_{t,c}^{\pm}(w)$: capacity factor for technology c in time period t;

$XE_{t,c}^{\pm}$: amount of generated electricity from power generation technology c in time period t (GWe);

p_{c} : probability of emission reduction target for technology c.

2.1.3.3 Manitoba

In order to solve the challenges in Manitoba energy systems, a large-scale integrated modeling system (IMS), which includes uncertainty analysis, the fuzzy-interval inference method (FIIM), and inexact energy model (IEM), was developed [7]. Taking into account local energy management policies, the target function is to minimize the total costs associated with energy services, activities and investments in the research province throughout the entire planning horizon. The constraints include the relationship between decision variables, capital costs, energy availabilities, investment costs, and energy production efficiencies. Besides, the planning horizon of this model is from 2003 to 2027 which includes five periods with five years in each period.

The advantages of the IMS are: (1) multiple technologies, sub-sectors, energy resources, and climate change impacts are integrated within a general modeling framework; (2) dealing with the interplay of impacts of climate change on multiple resources and energy subsectors within an EMS; (3) a two-step procedure is used to identify optimal adaptation strategies for the impact of an EMS on climate change; (4) addressing multi-level uncertain information related to adaptation planning and the climate change effect analysis; (5) seamlessly incorporating climate change effect analysis results within inexact adaptation planning.

For example, the advantage (2) is represented as follows: (a) the energy demand of end-user and the energy supply of renewable energy resources are fuzzy sets (e.g. $DAGC$) related to the different levels of climate change impacts; (b) the construction of fuzzy sets membership functions relied on the expertise and experience for experts and stakeholders.

$$Conv_{i,j,t}^{\pm} \times X_{i,j,1,t}^{\pm} \geq DAGC_{i,t}^{\pm} \qquad \forall i = 4, t, j \qquad (16)$$

Where

$X^{\pm}_{i,j,1,t}$: Amount of energy resource *i* consumed by sub-sector of agriculture *j* in period *t* (PJ)
$Conv^{\pm}_{i,j,t}$: Conversion efficiency of energy *i* consumed by sub-sector of agriculture *j* in period *t*
$DAGC^{\pm}_{i,t}$: The agriculture energy demand for energy resource *i* in period *t* (PJ)

2.1.3.4 Saskatchewan

In order to optimize the existing electricity power system, a multi-stage joint-probabilistic left-hand-side chance-constrained fractional programming (MJCFP) model is developed to deal with typical electric power systems issues with multi-uncertainties and alleviate the difficulty of managing climate change mitigation issues under risk analysis in Saskatchewan[8]. In detail, FP is firstly comprised by combining multi-stage programming framework to address trade-off problems among multi-objective issues. For better optimizing the stochastic problems, joint-probabilistic chance-constrained model are introduced to obtain the optimal decision-making results under uncertainties to reflect the risk under violating system constraints as well.

Typical advantages of the MJCFP are: (1) balancing contradictory objectives, socio-economic revenue and climate change mitigation, no need to change its original extent; (2) providing an effective connection between fractional optimization problems as well as reflecting economic and environmental interactions; (3) considering the randomness of carbon emission under limited conditions; (4) supporting detailed analysis of the inter-relationship between target ratios, climate change risks and profits; (5) effectively reflecting the dynamics and uncertainty of end-user requirements

A multistage fractional programming (MFP) problem can be formulated as follows:

$$Maxf = \frac{\text{SystemProfit}}{\text{CarbonEmissionAmount}} = \frac{\sum_{1}^{T}\sum_{1}^{D}\sum_{1}^{Q_t} p_q \cdot RE_{td} \cdot XDEM_{tdq} + \cdots + \sum_{1}^{T}\sum_{1}^{B} RP_{tb} \cdot PR_{tb} - \cdots - \sum_{1}^{T}\sum_{1}^{Q_t} p_q \cdot COI_t \cdot XEI_{tq}}{\sum_{1}^{T}\sum_{1}^{J}\sum_{1}^{Q_t} p_q \cdot EM_{tj} \cdot X_{tjq}} \tag{17}$$

where, p_q = probability of occurrence of scenario q; RE_{td} = electricity price for end-user d in period t ($/MWh); $XDEM_{tdq}$ = electricity supply for demand user d under scenario q in period t (GWh); RP_{tb} = unit revenue of byproduct b in period t ($/tonne); COI_t = cost of imported electricity in period t ($/MWh); XEI_{tq} = electricity import amount under scenario q in period t (GWh); EM_{tj} = carbon emissions intensity of generation type j in period t (tonne/MWh); X_{tjq} = electricity generation amount by power under scenario in period (GWh).

2.2 Theoretical framework for the CGE model

2.2.1 Production module and Trade module

The production module consists of capital, labor, energy and intermediate inputs for producting outputs. Constant elasticity of substitution production functions are employed to represent this module, as shown in Equation (18) [5,6].

$$QX_i = \alpha_i^a \left(\delta_i^a F_i^{\frac{\sigma-1}{\sigma}} + \left(1-\delta_i^a\right) E_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{18}$$

QX_i represents total output; α_i^a represents a scale parameter in the constant elasticity of substitution activity function; δ_i^a represents a share parameter of constant elasticity of substitution activity function; F_i and E_i represent two kinds of inputs respectively; σ represents the elasticity substitution parameter; i represents production activity sets.

Commodities are simultaneously exported and imported in the trade module. For domestic commodities and imports, domestic demands of these commodities are determined by constant elasticity of substitution utility function, as shown in Equation (19) [7,8].

$$QQ_j = \alpha_j^q \left(\delta_j^q QM_j^{-\rho_i^q} + \left(1-\delta_j^q\right) QD_j^{-\rho_j^q} \right)^{\frac{1}{\rho_j^q}} \tag{19}$$

QQ_j is labeled as the composite supply; QM_j represents the quantity of imported goods; α_j^q represents a scale parameter in the constant elasticity of substitution utility function; δ_j^q represents a share parameter; QD_j represents the domestic goods quantity; ρ_i^q represents the constant elasticity of substitution utility function exponent; j represents the goods sets imported and produced domestically.

Constant elasticity transformation function is adopted to choose between export and domestic market, as shown in Equation (20)[7,8].

$$QT_k = \alpha_k^t \left(\delta_k^t QE_k^{\rho_k^t} + \left(1-\delta_k^t\right) QD_k^{\rho_k^t} \right)^{\frac{1}{\rho_k^t}} \tag{20}$$

QT_k represents the composite supply; α_k^t represents a scale parameter in the constant elasticity of substitution utility function; δ_k^t represents the share parameter; QE_k represents the exported goods quantity; QD_k represents the domestic goods quantity; ρ_k^t represents the constant elasticity of substitution utility function exponent; k represents the goods sets exported and produced domestically.

2.2.2 Income and expenditure module

Households, the government, enterprises and the rest of the world are four economic agents considered in this report. The consumption function is based on the Stone-Geary utility function assumption, as shown in Equation (21) [5,7].

$$DH_i \cdot P_i = \gamma_i \cdot P_i + \beta_i \left(YH - \sum_i \gamma_i \cdot P_i \right) \tag{21}$$

DH_i represents the household demand for goods i; P_i represents the commodity i market price; γ_i represents the commodity i subsistence consumption level; YH represents the household total income; β_i represents the marginal propensity of commodity i consumption; i represents the goods sets.

2.2.3 Carbon tax module

Excise tax is the carbon tax which is imposed on fossil fuels based on the content of CO_2. The carbon tax levied on each fossil fuel is shown in Equation (22), and the Equation (23) can calculate the ad valorem duty rate [9,10].

$$CTAX_f = t_c QQ_f \varepsilon_f \tag{22}$$

$$t_{cf} = \frac{CTAX_f}{PQ_f QQ_f} \tag{23}$$

$CTAX_f$ represents a carbon tax levied on fossil energy f; t_c represents the carbon tax specific duty rate; t_{cf} is labeled as the ad valorem duty rate of carbon tax on fossil energy f; PQ_f represents the price of fossil energy f; QQ_f represents the total domestic consumption of fossil energy f; ε_f represents the carbon emission coefficient of fossil energy f; f represents the fossil energy sets.

2.2.4 Model closure and market clearing

According to the theory of general equilibrium, a CGE model represents the combination of factor market balance and goods market balance simultaneously. The equilibrium of income and expenditure means the equals between expenditures and revenue of all economies. The equilibrium of inputs and outputs requires each sectoral total supply to satisfy the total of intermediate use, domestic consumption, net export, and investment. Capital market clearing refers to the matching of savings and total investment in all sectors.

The modelling results

1 British Columbia

Figure 1 shows the optimal results for energy demands at the low demand level by sectors. For qs = 0.01, the supplies of natural gas are 7.9 PJ and coal, diesel, fuel oil, biomass for power generation would be 0, 0.08, 0.16, and 0.79, respectively. Those energy resources embody the importation amount at 6.21, 0, 0.85, 4.78, and 4.64 PJ. The utilization would be 1386.7, 387.8, 625.8, 40.53, 312.2, and 714.77 PJ for natural gas, diesel, gasoline, liquefied petroleum gas (LPG), fuel oil, and biomass, respectively. Under different qs levels over the planning horizon, the scheme of energy supply for all technologies can be further studied.

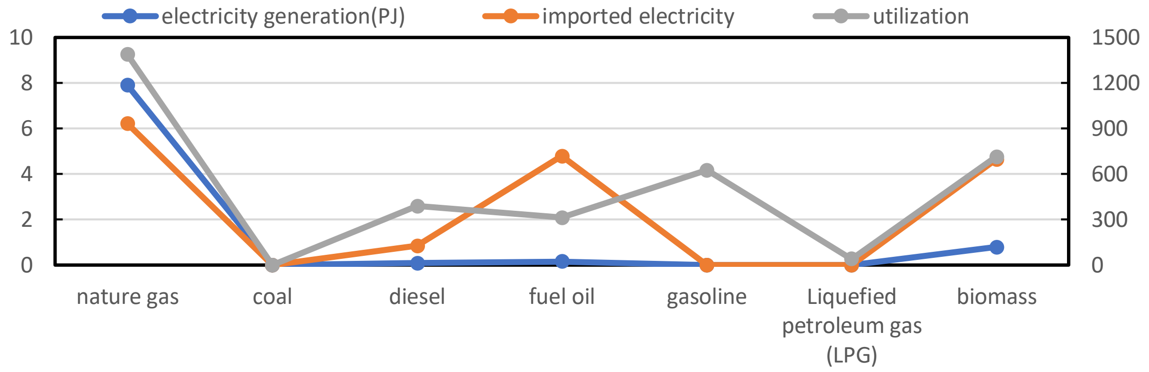


Figure 1 Energy demands by sectors in British Columbia, qs=0.01

According to the sustainability of energy types under q_s = 0.01, Figure 2 and Figure 3 illustrate the energy allocation schemes for non-renewable and renewable technologies, which shows the power generation would keep the steadily rising trend to meet the future power demand. It is worth mentioning that the hydropower is dominating the producing duties in the energy system due to resources's abundant availability and large capacity in the province of British Columbia. For example, the electricity contributed by hydropower would be 931.09, 989.13, 1042.23, 1092.45, 1137.93, and 1178.06 PJ, respectively under qs = 0.01. Furthermore, British Columbia is located at the west coast of Canada, the geographical advantage brings abundance of wave power. Therefore, although the demand rate is low, the wave/tide power facility would still produce 263.82, 280.26, 295.31, 309.54, 322.43, and 333.80 PJ as the timing plan. The Power produced from the wave power could play an significant role in supplying electricity for British Columbia. Refer to non-renewable electricity supply patterns, natural gas-fired plants would support 12.28, 13.05, 13.75, 14.41, 15.01, and 15.54 PJ over the planning period.

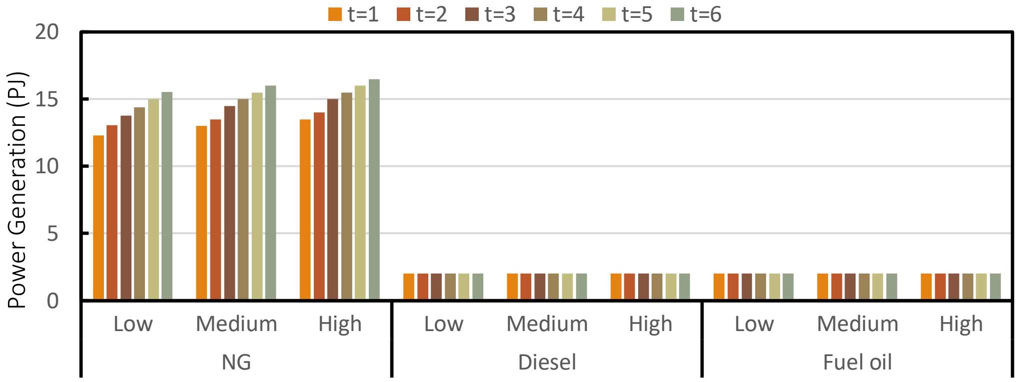


Figure 2 Power generation for non-renewable energy

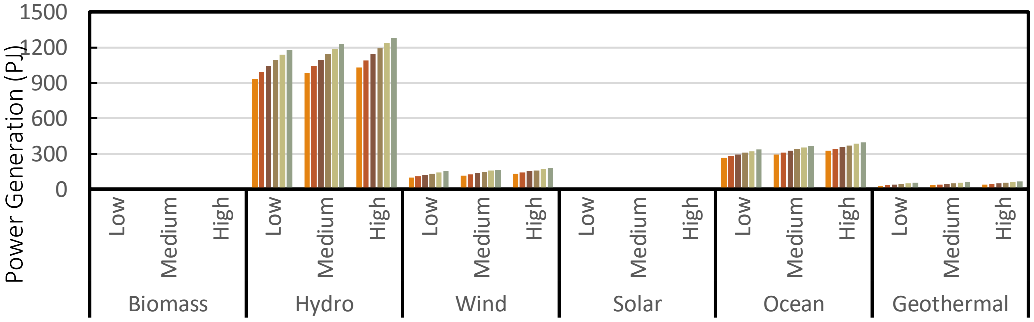


Figure 3 Power generation for renewable energy

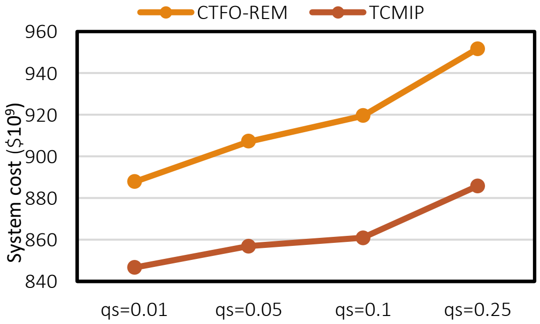


Figure 4 System costs for different models

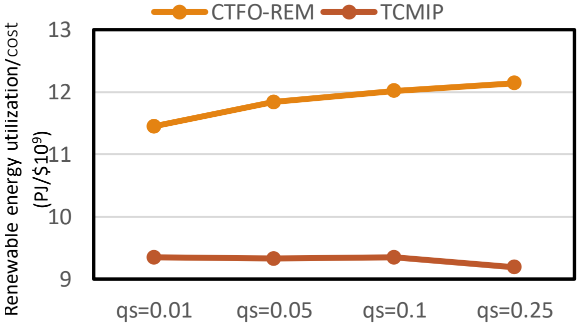


Figure 5 System efficiencies for different models

Moreover, in order to highlight the advancement of the proposed model, the comparison of system costs corresponding to CTFO-REM and multiple constraint-violation levels TCMIP model has shown in Figure 4. As the gradually escalating qs from 0.01, 0.05, 0.10 to 0.25, the system cost for least-cost TCMIP model are $\$846.64*10^9$, $\$856.88*10^9$, $\$860.95*10^9$, and $\$885.78*10^9$ correspondingly. Under a range of qs levels, the system costs for TCMIP model are slightly lower than the developed CTFO-REM model from the results. Nevertheless, CTFO-REM model conveys the higher renewable energy utilization per unit of cost, which is 11.86 PJ per $\$10^9$, than 9.3 PJ per 10^9 \$ of the least-cost TCMIP model.

2 Alberta

The results of energy system planning for the province of Alberta are presented in five periods (T1, T2, T3, T4, and T5), and the baseline level is the results of the first two periods (2003-2007 and 2008-2012). Figure 6 illustrates the optimal allocation patterns of major energy resources in Alberta in the five planning periods. Results imply that the utilizations of major energy resources (e.g., coal, bitumen, and natural gas) keep the rising trends. The exported amount of coal, natural gas, and crude oil would also increase. The activity of coal mining would remain at a relatively stable rate. The increasing exported amount of coal is to meet growing requirements, which reflects a descending trend of coal consumptions in the province of Alberta. The extraction of NG would increase steadily in the future 3 periods, and the results are shown in interval values of [5384.3, 5429.1] PJ, [6873.7, 7057.8] PJ, and [8692.2, 9175.1] PJ, respectively.

The solution of electricity production in Alberta is given in Figure 7. The key sources of power are coal-fired and natural gas-fired power plants over the planning horizon. Coal-powered technology plays an essential role due to its lower cost compared to other electricity sources, but it produces a high amount of GHG emission. By contrast, power produced by natural gas would have a significant increase. Besides, fuel oil-based power would be generally utilized with a neglectable scale to satisfy certain power demand. Refer to renewable power technology, such as wind, solar, hydro and biomass-based power, they would remain a rising trend in the future, limited by the GHG emissions reduction requirement. Specifically, the largest portion of renewable energy is occupied by wind power, from the current 7.55 PJ to 50.70 PJ. Solar power is limited by its capacity cost and would not be adopted on a large scale, only 0.18 PJ in period 4. Hydropower would also increase in the future. Considering most of the remaining hydropower reserves are at the far north region, further resources exploitation would highly depend on the support of a new transmission system. Nuclear power, due to its high investment and operation cost, would not be developed in this model.

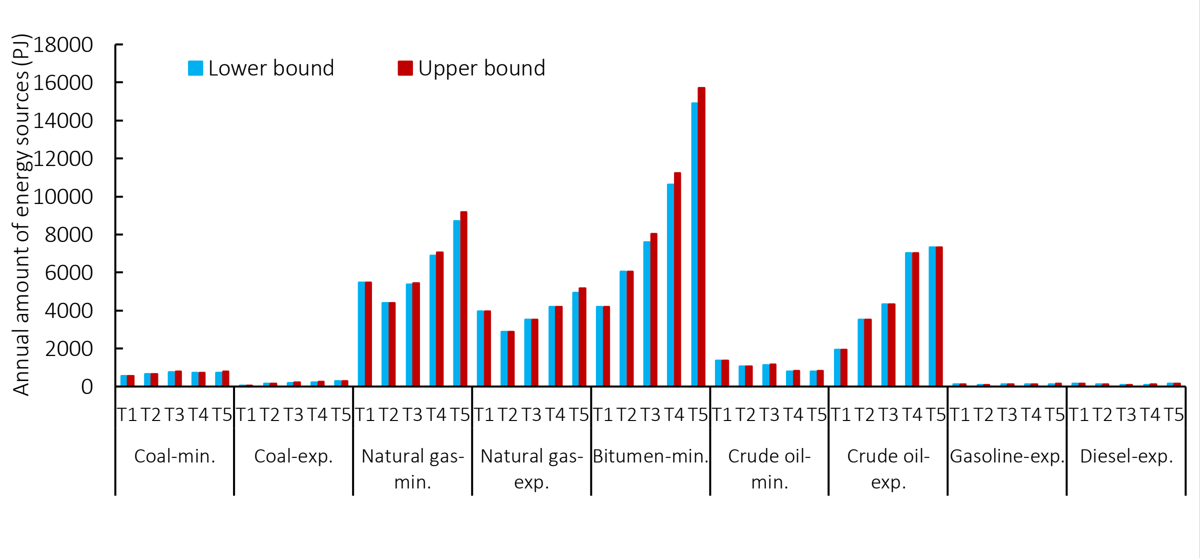


Figure 6 Allocation of major energy resources in Alberta in the planning periods

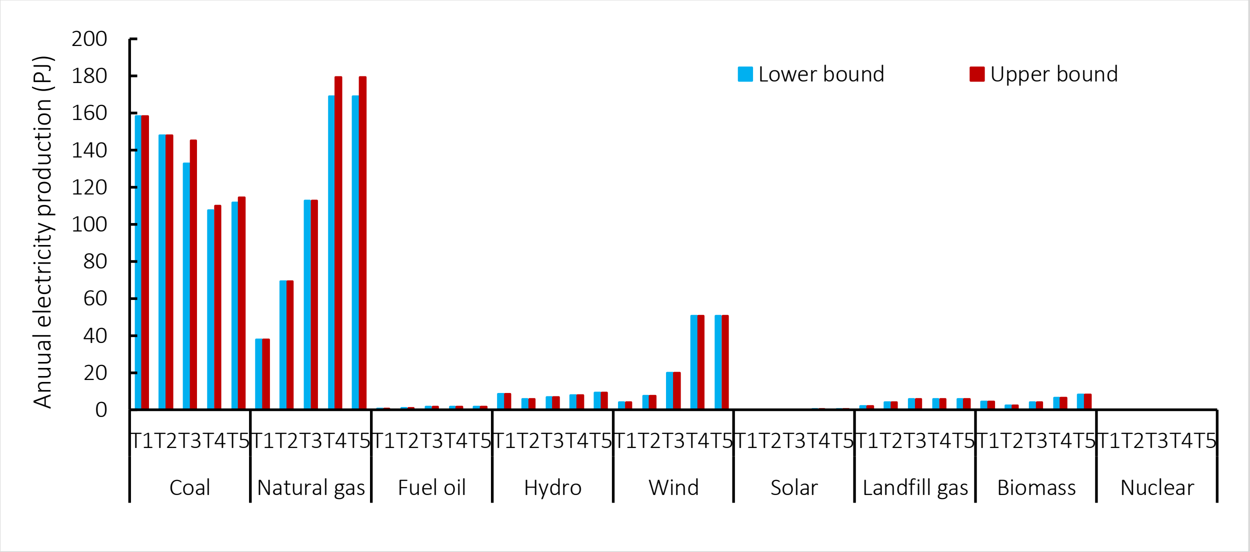


Figure 7 Electricity production in Alberta in the planning periods

Table 1 shows the expected total system costs for the system activities over the whole planning horizon. The results are embodied as interval values, reflecting the interactive impacts by the uncertain inputs (such as the uncertainties of energy demand, market fluctuation, resource availability, and offset credits availability). The lower bounds could be achieved when a set of conservative schemes are adopted as the decision alternatives. For instance, when the costs for activities of energy supply, capacity expansion, electricity production, processing capacity expansion, petro/biofuel processing, and demanding are at lower bound 1764586, 103457, 9614, 957368, 38061, and 581268 million$, the system cost can be attained as 3482218 million $.

Table 1 Total system costs for the 5 planning periods

Activity	Total system costs (million $)	
	Lower bound	Upper bound
Energy supply	1764586	1916953
Electricity production	9614	10352
Generation cap expansion	103457	117467
Petro/biofuel production	38061	39855
Processing cap. expansion	957368	1209685
Demand technologies	581268	625214
Total	3482218	3739498

3 Manitoba

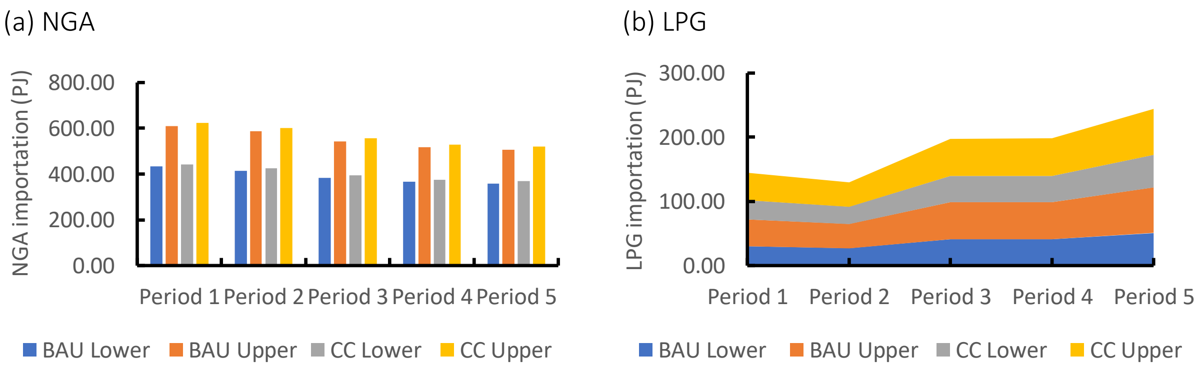
Table 2 shows the values of the objective function and their changes compared with the BAU case. As the uncertainties over climate change reflects, changes in energy-related spending would be observed mainly in electricity generation sub-sectors, residential, and commercial. In detail, the total spending in the electricity generation sub-sectors, residential sector and commercial would be increased from CAD [718.97, 2253.75], [215.19, 428.97], and [161.98, 322.84] to [752.00, 2297.05], [222.15, 442.80], and [166.55, 332.00] ×10^8, respectively. Among them, electricity would be the most sensitive to the impact of climate change, increasing by 4.60 and 1.92%, respectively, between the lower and upper bounds. This corresponds to 2.32% and 1.43% increments under the lower and upper bounds of the total system cost. In terms of transportation subsectors and the industriesial, there would be no noticeable impacts on climate change. Therefore, there will be no major adaptation to the impact of these two subsectors.

Table 2 Energy related expenses under BAU case and climate change

10^8 CAD		C1	C2	C3	C4	C5	Total
BAU	Lower	215.19	161.98	595.92	229.08	718.97	1921.14
	Upper	428.97	322.84	1187.79	456.47	2253.75	4649.82
CC	Lower	222.15	166.55	595.90	229.10	752.00	1965.70
	Upper	442.80	332.00	1187.80	456.45	2297.05	4716.10

Note: BAU = Business as usual and CC = Climate change

The imports of natural gas, fuel oil, LPG and heating oil will be adjusted to some extent as Manitoba's energy sector's adaptation measures for the integrated effects of climate change (Figure 8). In detail, the adopted energy resources imports would increase slightly. This is mainly due to the responses to increased end-user demand. For instance, the imports of natural gas would be [432.60, 610.65] and [442.65, 624.90] PJ under the case of BAU and the case of climate change, respectively. In the second to fifth period, in the case of BAU, the imports of this energy would be [415.05, 585.95], [383.65, 541.60], [365.7, 516.3], and [359.35, 507.25] PJ, respectively. In the case of climate change, these amount would correspondingly increase to [424.85, 599.85], [393.3, 555.25], [374.75, 529.00], and [368.45, 520.1] PJ, respectively (Figure 8(a)). The imports of LPG and fuel oil will increase slightly over the same period because of the relatively small share of LPG and fuel in the residential and commercial sectors(Figure 8 (b)(c)). Under BAU case and climate change, heating oil would account for a small portion of the province's total energy consumption. Such a large amount of heating oil will be consumed mainly in residential and commercial sectors of the province, especially in water heating, commercial, and residential space (Figure 8(d)).


(a) NGA

(b) LPG

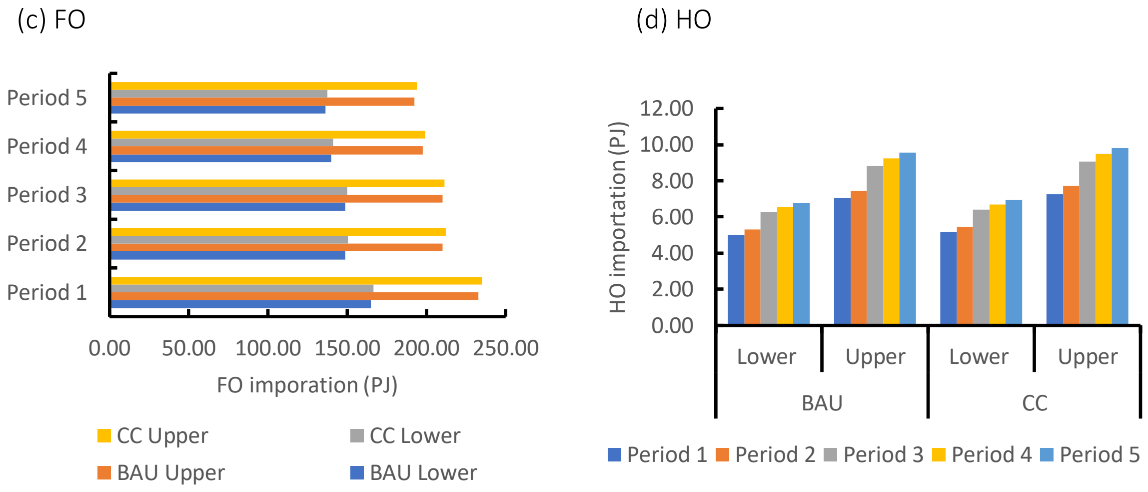


Figure 8 Energy importation under BAU case and climate change (NGA = Natrural gas, LPG = Liquefied petroleum gas, FO = Fuel oil, HO = heating oil, BAU = Business as usual, and CC = Climate change)

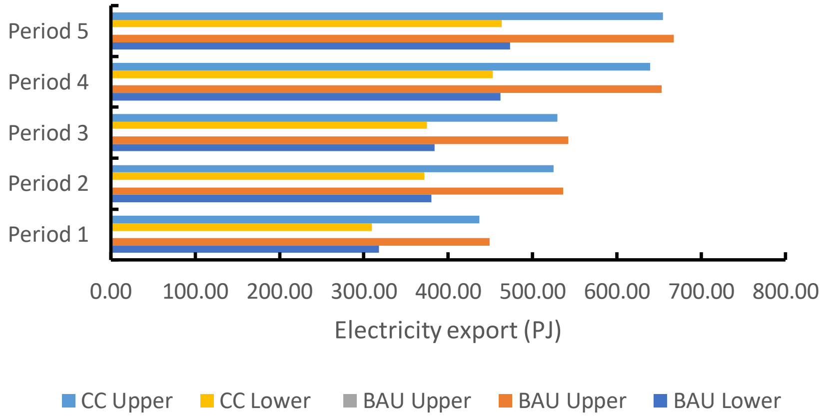


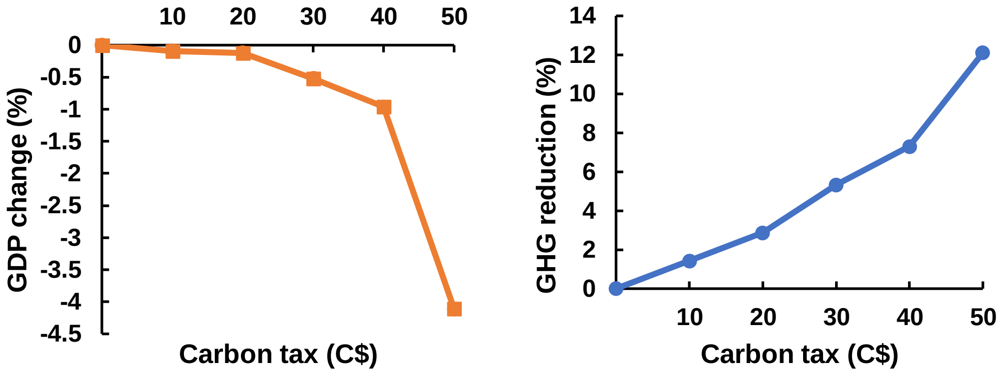
Figure 9 Electricity export under BAU and climate change (BAU = Business as usual, CC= Climate change)

Electricity exports would be partially affected in part by climate change (Figure 9). In General, the power output from the province is less than the power output in the BAU case. It is because that the end-user demands for electricity increase and the renewable availabilities for electricity production decrease under climate change in the province. For example, in the first period, [318.1, 449.15] PJ of power would be exported from Manitoba (especially to the United States, Ontario, and Saskatchewan). During the same period, this amount will decrease to [309.60, 437.10] PJ under climate change.

4 Saskatchewan

4.1 Modelling results of CGE model [15]

4.1.1 Inter-relationships among carbon tax, GDP and GHG reduction



(a) (b)

Figure 10 The inter-relationships between carbon tax and GDP change (a) and GHG reduction (b)

As shown in Figure 10, the effects of carbon tax on total GHG emission mitigation and GDP change were quantified based on the CGE model. GDP change reduced due to the carbon tax increases as shown in Figure 10 (a). On the contrast, it is seen from Figure 10(a) that the carbon tax has positive effects on emission reduction.

Figure 10(a) reveals the effects of five carbon tax scenarios on GDP change, which quantifies the correlation between economic growth and carbon tax. When carbon tax is less than C$ 30, the change in GDP is relatively low. This suggests that a relatively low carbon tax will not have a significant impact on the economy. In scenarios 3 and 4, the GDP falls faster as the carbon tax grow continuously. The GDP will fall sharply when the carbon tax is C$50/tonne. The GDP change for scenario 5 would not be considered acceptable for the reason that the GDP increase of Saskatchewan was approximately 2% in 2015.

It can be seen from Figure 10(b) that the application of carbon tax has a positive effect on reducing GHG emissions. It is obvious that carbon tax is an operative way to mitigate the GHG emissions. It is also worth noting that the GHG emission mitigation rate is increasing along with the carbon tax rate. Comparing Figure 10(a) and (b), the impact of carbon tax on GHG emission mitigation is smaller than that of carbon tax on GDP change.

In Saskatchewan, a separate carbon tax may not be the most cost-effictive policy to achieve GHG emission mitigation goals. Therefore, it is vital to analyze how the carbon tax affects the economy to support the climate change policy decisions.

4.1.2 The impacts on the macro economy

In this study, as shown in

Table *3*, seven macroeconomic variables in five scenarios are conculated to analyze the effects of carbon tax to macro economy. A carbon tax has all negative effects on real GDP. Since the the sum of government consumption, household consumption, total savings and stocks, total investment, imports and exports are equal to real GDP, these six indicators are calculated to investigate the reasons interpreting the economic changes. From

Table *3*, it can be seen that government consumption and household consumption will decrease under a carbon tax. When the carbon tax reaches C$40/tonne, government consumption and household consumption will decline by 0.11% and 0.25% respectively. Thus, economic depression will lead to the decline of household income, which will further cause a decline of consumption. For the government, a reduction in production will also reduce income such as taxes and transfers. Conversely, the reduction in consumption will lead to a reduction of production from demand aspects.

Saskatchewan exports almost all of its emission-intensive industry products to other countries and provinces. Thus, the exports will reduce due to the production decrease in these industries. For instence, exports will decline by 0.14%, when the carbon tax is C$ 40/tonne. When the carbon tax rate is C$50/tonne, exports will decrease by 2.1%, which is a significant incremental decrease. The impact on exports is obvious than that on import. For example, when the carbon tax rate is C$50/tonne, imports increase by 0.22%. Although the domestic production will decline, the total consumption will also decrease, leading to a relatively low growth in imports.

Table *3* also shows that the savings and total investment and stocks will all decline under a carbon tax due to the capital market equilibrium. The effect of a carbon tax on total investment is more remarkable.

To sum up, the carbon tax has negative effects on government consumption, household consumption, total savings and stocks, total investment, and exports. It encourages people to import services and goods. The change in household consumption, total investment, and exports change notablely, when under certain carbon tax rates. In other words, the entire economy is affected by the carbon tax mainly through these three aspects. When implementing a carbon tax in Saskatchewan, these industries that can be easily imported from other regions should be protected to avoid the significant output reduction.

Table 3 The impacts on macroeconomic variables

	Scenario 1	Scenario	Scenario	Scenario	Scenario
Carbon tax rate (C$/tonne)	10	20	30	40	50
Real GDP (%)	-0.09	-0.12	-0.52	-0.96	-4.11
Household consumption (%)	-0.02	-0.03	-0.15	-0.25	-0.32
Government consumption (%)	-0.02	-0.03	-0.09	-0.11	-0.21
Total investment (%)	-0.02	-0.03	-0.17	-0.24	-1.10
Total saving and stocking (%)	-0.01	-0.01	-0.02	-0.04	-1.16
Export (%)	-0.01	-0.01	-0.03	-0.14	-1.10

Import (%)	0.01	0.01	0.06	0.18	0.22

4.2 Modelling results of optimization model

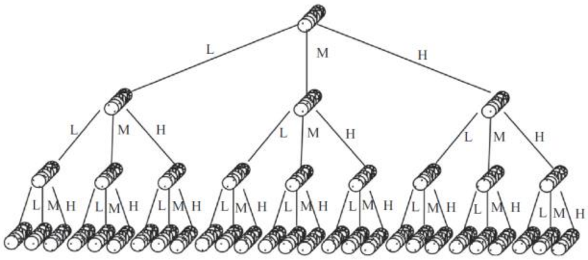


Figure 11 Scenario tree for electric power system planning

For this case, the multi-layer scenario level (shown in Figure 11) with a hierarchical structure could be developed for indicating random end-user power requirements, which leads to three scenarios in period 1 (2016-2020), nine scenarios in period 2 (2021-2025), and twenty-seven scenarios in period 3 (2026-2030). Moreover, sets of chance constraints for the carbon emissions objective of the three periods are taken into account, which could conducive to explore the risk of violating the emission permit constraints and produce desired power distributions and generation patterns. Nine scenarios including nine EPS models are scrutinized on the basis of multiple joint and individual probabilities. Three rising joint probabilities (p_k = 0.01, 0.05 and 0.1) specify an increasing risk of violating the constraints of carbon emission limitation goal. At each level of joint probability, there were three groups of individual probabilities for example, in conditions 1, 2 and 3. Subsequently, for each risk level, there were 39 scenarios to be investigated under three planning periods.

The MJCFP model offers the solution to the electricity generation plan under p_k = 0.1. This indicates that gas power and wind power are two major sources to deal with electricity requirement variations. In addition, on the basis of low demand levels in the first period, amounts of power generated by six transformation technology types would be 18681.82, 5003.711, 1567.67, 26266.75, 1170.25 and 1451.97 GWh when the demand levels are medium in period two. In general, for meeting power demands, generation amounts of different power categories are rising. However, coal-fired power generation decreases because there are several coal-fired plants being retired basing on new federal carbon mitigation regulations.

In terms of electricity generation capacity expansion, the solutions indicate that any change in p_k could yield varying carbon dioxide emissions and thus leading to various management patterns, especially in capacity expansion schemes. Figure 12 offers the demonstration of the optimized expansion scheme under condition 2 (when p_k = 0.01), 8 and 9 (when p_k = 0.1). Under condition 8, existing capacities of wind power might be inadequate to satisfy energy demands. The wind power facilities could be expanded with a capacity of 300 MW in period 1 and another 300 MW in period 2, which are varied from those under condition 2. On the contrary, under condition 2, a capacity of 100 MW could be added to the wind facilities in period 1, while gas generation conversion technology could be expanded with a capacity of 500 MW in period 2. Besides, the expansion plans would differ from individual probability (p_s) of each carbon emission limitation (even under the same joint probability level).

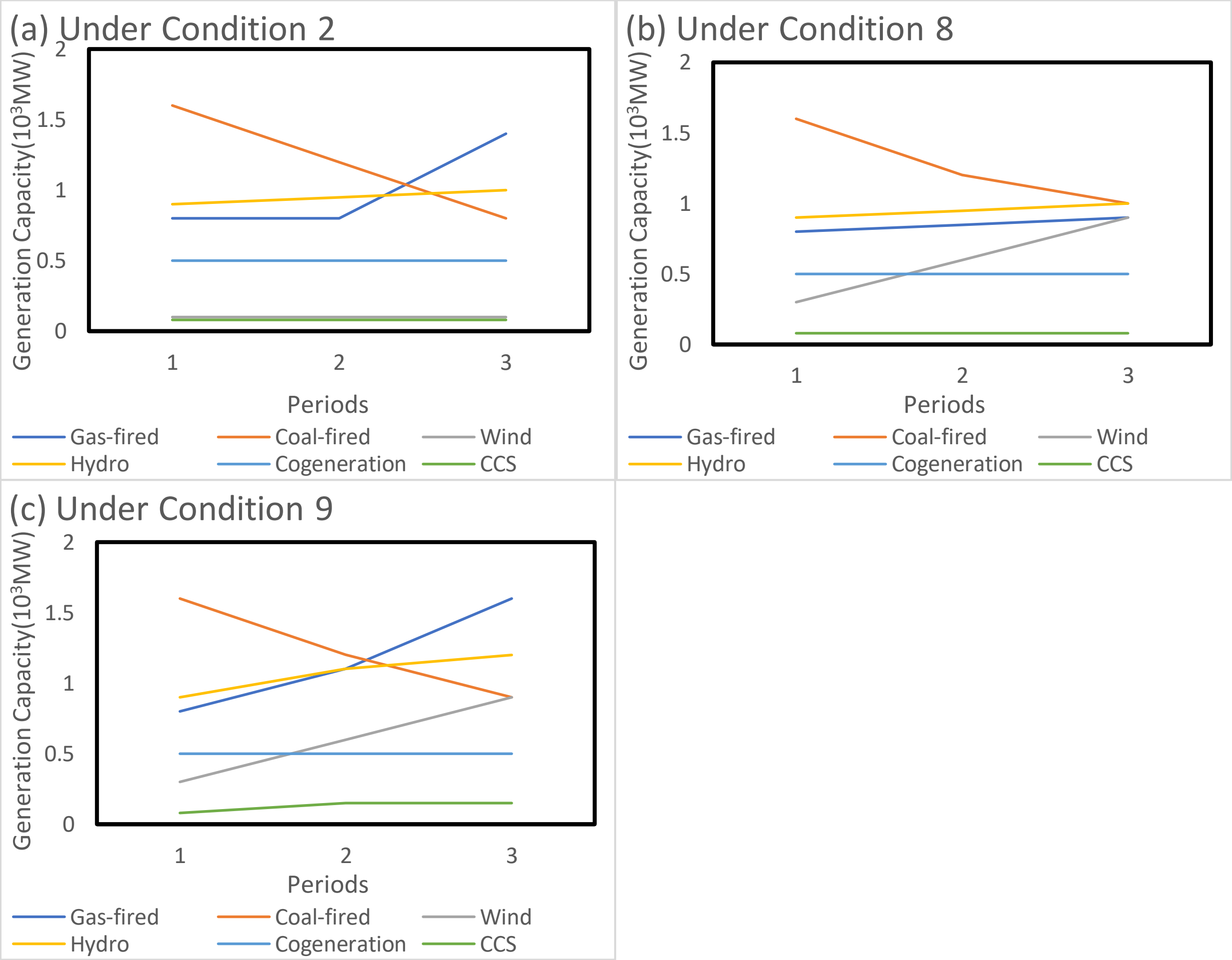


Figure 12 Solutions of capacity expansion scheme for electric power plants under p_k = 0.01 (condition 2), p_k = 0.1 (condition 8, condition 9).

Additionally, the results of MJCFP model could suggest that a higher p_k level could correspond to a higher optimal ratio at the cost of the environment. Although, the power generation schemes obtained from the MJCLP model are generally different because of the existence of the uncertainties and varied probabilities. In conclusion, the coal-fired power would become the main electrical power generation form, yielding to stronger carbon intensity by pursuing higher economic competitiveness.

Its place in the ecosystem

1. Usage

In short term, it is anticipated that the proposed technologies can be transferred to other Canadian jurisdictions to generate more extensive impacts, since different regions in Canada are facing similar challenges of curbing greenhouse gas emissions, adaptation to climate change, and clean energy transitions. Canadian Energy Modeling System has been successfully applied to Eastern and Northern Canada, such as Waterloo-Kitchener Region, Toronto-Niagara Region, Ontario, and Yukon. Applications of the proposed techniques to more Canadian cases will be conducted to help industry and government improve their effectiveness in managing complex energy-related problems, and will lead to new knowledge in the field of energy systems engineering.

In long-term, the Canadian Energy Modeling System will be developed based on the proposed model. Impacts of climate change, population growth and economic development could be effectively reflected. The results provided scientific bases for energy policy formulation, environmental management, and climate change adaptation. Moreover, a Multi-Region Canadian Modeling System will be developed by integrating the separate models and enable the material and economic flows among all provinces and jurisdictions. The reflection of the interactions among various areas will further enhance the capacity of the model. Particularly, the developed methodologies can provide supports for addressing some of the most challenging problems associated with entire Canada, such as clean-energy transition, GHG mitigation responsibility allocation and so on. To be specific, impacts of different emission-reduction policies on various objectives at provincial, regional and national levels will be evaluated. Compound risks associated with dependent uncertainties under various socio-economic conditions and policy scenarios will be assessed within a multi-level and spatially-distributed framework. The results will provide scientific bases for assessing implications of different regional and national policies on GHG emission, socio-economic development, and environmental welfare, and for facilitating policy formulation with consideration of interprovincial interactions.

A number of policy alternatives regarding emission reduction and socio-economic development at multiple administrative levels will be generated, which will then contribute to improved effectiveness in policy making at national level.

- British Columbia

The multi-angle CTFO-REM model descripted above is the first attampt of using energy optimization method to address British Columbia’s energy system management problems. The proposed model can help maximize renewable energy resources utilization with potential low system costs and environmental impacts, and can deal with the uncertainties existing in both the objective and constraints. As the expectation, the proposed method would be an effective tool for supporting practical energy-related management problems and can be extended to other administrative areas. Moreover, the CTFO-REM method could further integrate other uncertainty technologies like fuzzy set and interval analysis to better characterize uncertainties exsited in the processes of problem definition as well as model formulation.

- Alberta

Alberta is Canada's largest GHG emitter and there are some serious issues in its energy-environment system. Due to the imbalance between its energy demand and supply, energy imports, exports and capacity expansions are necessary. Meanwhile, the environmental problems, such as GHG emissions (mainly CO_2, CH_4, and N_2O), caused by energy mining, production and consumptions, should be effectively controlled and mitigated by reasonable management planning to meet the national GHG mitigation target. Currently, sectors of bitumen extraction and upgrading, coal/natural gas power generation, and transportation contribute the largest amount of GHG emissions. The periodical targets of GHG emissions could be satisfied with optimized system planning. The IFTCP-IEES model developed for Albert could also be applied to other areas. In the future, the effectiveness of various kinds of federal and provincial GHG mitigation policies and measures should be simulated and tested to determine the best solution for the sustainable development of Alberta's energy system.

- Manitoba

The developed model has been applied in Manitoba to prove its applicability and effectiveness. Practical solutions, which can reflect the complex trade-offs between the province's various administrative objectiveshave been generated. The results show that (a) adaptation plans should be adopted to alleviate the province's high dependence on renewable energy, thereby respond to different impacts of climate change on both energy demand and supply; (b) energy allocation/production plans in power-generation sub-sectors, residential and commercial will be sensitive to climate change. Therefore, in the systematic context of this province, it is of great importance to identify the integrated impacts of climate change and the corresponding adaptation programs.

The majority of electricity in Manitoba is generated from hydropower stations scattered throughout many watersheds. Variations in rainfall-runoff relationships, hydrological regimes and end-user water demands due to climate change could be studied through hydrological models. Therefore, the integration of hydrological models into climate change impact analysis will greatly improve the applicability of the study. Moreover, due to the complexity of Manitoba's electricity management system, the data required is extensive. Although most of the data collected were relatively accurate, deterministic numbers or narrow intervals, some of them are highly uncertain. Thus, improving the quality of input data through further investigation and verification will help improve the reliability of the generated solution.

- Saskatchewan

As the second largest electric facilities service area in Canada, the province of Saskatchewan has a complex energy system to support various kinds of energy-related activities. Moreover, along with the high GHG emissions, the province faces great pressure in mitigating industrial emission under the regulation of federal government. The results from the abovementioned optimization model showed that, from 2015 to 2030, the power consumption is predicted to grow steadily according to the provided power allocation solutions for all end-user sectors.

In future works, the proposed optimization model could be integrated with CGE model to simulate both energy- and environment-related issues and socio-economic activities. Although several difficulties need to be solved for the integration of these two methods (e.g. , matching of the different scales), the solution could be definitely more suitable for real-world conditions. With the integrated optimization based CGE model, a lot more suggestions could be provided for the decision makers of the Province of Saskatchewan or even the other regions around the world. For example, the optimization modeling for electricity generation management under the condition of carbon tax policy is desired to make not only for maximizing the profit for the whole electricity generation system but also for quantifying the contributions of such policy to socio-economic benefits in the whole society.

2. Possible synergy with other models

The proposed model will imply R&D for a range of innovative technologies for energy systems analysis and risk management under interactive uncertainties. It will facilitate advanced studies for stochastic analysis, factorial design, risk management, inexact optimization, and their integrations. Different methodology can be integrated into a general optimization framework; they are capable of addressing multi-level uncertainties in modeling parameters and the interactive relationships.

Factorial analysis has been widely used as an approach for revealing interactions among factors of interest as well as the related contributions to system performance. Comparing with single factor sensitivity analysis, factorial analysis is much more efficient and it can provide more insights in terms of the interation effects. For example, in a factorial analysis with three factors a, b and c, the three main effects (a, b, and c) and interaction effects (ab, ac, bc, and abc) will be tested and analyzed. The obtained details will further support the energy planning decisions.

Based on Ito's calculus, stochastic analysis is used to reflect the uncertainties in the real world. In energy models, all of the parameters, variables, and scenarios can be uncertain, leading the requirement to introduce stochastic analysis into energy model. The integration of energy model and stochastic analysis will be capable of tackling probabilistic uncertainties, and revealing interdependences of various uncertainties as well as their impacts on system performance.

In addition, factorial analysis and stochastic can be integrated into energy model framework. The concept of multi-level factorial analysis will be presented to tackle various combinations of different levels. It will improve upon the conventional stochastic method through reflection of the effects of multiple interactive factors on different dependent variables.

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