A SIMULATION MODEL FOR CANADA-US CLIMATE POLICY ANALYSIS

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ABSTRACT

Forecasting the effectiveness and economic impacts of public policies to tackle climate change requires sophisticated energy-economy models. This research is a step towards the integration of bottom-up technology models and top-down macroeconomic models. A simulation model of the energy-economy of Canada and the United States is used to account for how the combined energy system of both countries is likely to respond to Canadian and US policy. Various climate policy scenarios are simulated and the model forecasts how energy trade between Canada and the US might change due to the policies. The results demonstrate that modelling the combined energy-economy of multiple countries is an important component of climate policy analysis, especially for Canada.

Keywords: Climate policy; economic modeling; greenhouse gas emissions; carbon tax; energy consumption; energy supply; energy trade

Subject Terms: Climatic changes -- Government policy -- Canada; Climatic changes -- Government policy -- United States; Greenhouse gas mitigation -- Government policy -- Canada; Environmental Policy -- Economic aspects

EXECUTIVE SUMMARY

This report describes research to evaluate the effectiveness and economic impact of public policies to reduce greenhouse gas emissions in Canada and the US. A model of the combined energy-economy of both countries is used to simulate various policy scenarios and to understand how climate policy affects energy trade. The model is a step toward the development of simulation models that integrate bottom-up technology modelling and top-down economic modelling capabilities.

Estimating the cost and effectiveness of climate policies is difficult because there is uncertainty in the costs and benefits of technologies, especially in future costs and benefits; modelling human behaviour and decision-making is difficult; and the economic effects of environmental policies may be widespread and diverse.

The CIMS model has a detailed representation of energy technologies used in all sectors of the economy.[1] The model forecasts energy demand and emissions by simulating the consumption of energy services and the choice of energy-using technologies. It uses a market share function to simulate real-world preferences and realistic decision-making behaviour. Policies such as a carbon tax or an emission cap and trade system are simulated by including the emission price in the cost of technologies.

However, the existing model is limited by its assumptions about energy trade. This research is motivated by the desire to model larger regions and trade between regions. A combined model of the US and Canada is especially important for Canadian climate policy analysis because Canada's economy is deeply integrated with that of the US.

The project involved (1) building models of US and Canadian energy use, (2) connecting the models to energy supply models using a model of international energy

[1] CIMS is the name of an energy-economy simulation model developed and maintained by the Energy and Materials Research Group at Simon Fraser University, BC, Canada.

trade, and (3) using the integrated model to simulate different scenarios of future US and Canadian climate policy.

To take account of changes in supply and demand when climate policies are adopted, I simulate trade in crude oil, natural gas, electricity and refined petroleum products between Canada, the US and the rest of the world. The trade model is based on the Armington assumption that products of different countries may be treated as imperfect substitutes. The model simulates how energy imports and domestic production in the US and Canada change when there are changes in energy demand or in the costs of energy production.

Policy makers are interested in the cost of reducing greenhouse gas emissions. Marginal abatement cost curves for the US and Canada show how much emission abatement opportunity exists at a given abatement cost. Results for the US suggest that 1.7 billion metric tonnes of greenhouse gases could be avoided in 2030 at a cost of 50 dollars per tonne or less. A greater percentage of emissions are avoidable in the US than in Canada with the same emission price. This is due to the larger amount of low cost emission abatement opportunity in the US electricity generation sector.

I simulate various climate policy scenarios in the US and Canada and analyse their effect on trade and emissions. In a policy scenario where the emission price rises slowly and reaches 60 US dollars per tonne by 2035, growth in emissions in Canada is slower than business-as-usual but total emissions continue to increase. In a policy scenario where the emission price rises to 120 dollars per tonne, emissions begin to reduce after 2025. Only in an aggressive policy scenario where the emission price rises fast and reaches 162 dollars do emissions reduce to a level below the 2005 level.

To consider the effect of US climate policy on Canada's efforts to reduce emissions, I compare scenarios where Canada and the US have an identical emission price with scenarios where only Canada has a price on emissions. When the US has an identical emission price, climate policy in Canada is 12 percent less effective in reducing emissions. This is because of changes in energy production and trade. When there is a price on emissions in the US, demand for energy imports is higher. Some of that demand is met by Canadian production. Higher output in energy production sectors leads to additional emissions in Canada.

When there is a policy in Canada only, emissions in the US are greater than business-as-usual. This is because emission reductions intended by the policy in Canada leak to the US and the rest of the world. Canadian energy production is lower and US energy production is higher. I found that the “leakage rate” to the US is about one quarter of emissions reduced in Canada.

Policy makers also want to know whether policies are politically acceptable. The maximum energy price increases as a result of climate policies are in the range 20 to 120 percent of the business-as-usual price. The natural gas price experiences the biggest increases. However, I do not consider what happens to the revenue generated by an emission price, which could reduce the impact of high prices.

The simulation results demonstrate that the model is able to provide information on the cost, effectiveness and economic impacts of climate policies. The results confirm that an integrated model of energy supply and demand between regions can account for changes in energy supply, demand and trade, which is useful for Canadian policy analysis. The ability to simulate US policy allows Canadian policy makers to determine the benefits of policy co-ordination with the US.

The results are sensitive to uncertain parameter values in the trade model and the model has a series of shortcomings that could be addressed. Nevertheless, this research is a step towards a hybrid simulation model for energy-environment policy analysis that combines the capabilities of bottom-up technology models and top-down macroeconomic models.

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ABBREVIATIONS

AEO	Annual Energy Outlook
BAU	Business-as-usual
BEEM	Building Energy End-Use Model
CA	Canada
CBECS	Commercial Buildings Energy Consumption Survey
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
CGE	Computational general equilibrium
CIMS	Canadian Integrated Modelling System
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EIA	US Energy Information Administration
EMRG	Energy and Materials Research Group
FLCC	Financial lifecycle cost
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoule
IGCC	Integrated gasification combined cycle
LRAC	Long-run average cost

MECS	Manufacturing energy consumption survey
NEB	National Energy Board
NEMS	National Energy Modelling System
PJ	Petajoule
RCI	Residential, commercial and institutional sector
ROW	Rest of the world
RPP	Refined petroleum products
SGM	Second Generation Model
US	United States

CHAPTER 1: INTRODUCTION

This report describes a research project to forecast the effectiveness and economic impact of public policies to reduce greenhouse gas (GHG) emissions in Canada and the United States (US). Canada's economy is deeply integrated with the US economy, so regulatory efforts by Canada to tackle issues such as climate change must take into account how the combined economy of both countries is likely to respond. US policy on environment and energy also affects the outcome. The research uses a model of energy supply and demand in the US and Canada to investigate the effects of various climate policy scenarios and to understand how energy trade might change due to policy. The model is a step toward the development of hybrid simulation models that integrate bottom-up technology modelling and top-down economic modelling capabilities.[2]

Energy supply and demand models of the US and Canada are used to simulate how technologies, energy use and emissions, might evolve over the next 25 years if regulators put a price on greenhouse gas emissions. The models are built with CIMS, an energy-economy modelling framework that simulates the behaviour of consumers and producers and the evolution of energy-using technologies in the economy.[3] The models are linked by a partial-equilibrium model of energy supply and demand.[4] I use the integrated model to consider how different policy scenarios in each country and different assumptions about energy trade influence forecasts of emissions and energy use. The

[2] Top-down and bottom-up are terms used to describe two different approaches to modelling energy-environment policy. Top-down models are models of the macro-economy that tend to use the historic behaviour of the economy to make forecasts of future behaviour. Bottom-up models are detailed engineering models of energy technologies that aim to simulate how new and alternative technologies are adopted. See Böhringer (1998) for an introduction to top-down and bottom-up modelling, and the special issue of Energy Journal (Hourcade et al., 2006) for a review of recent work to integrate the two approaches.

[3] CIMS is the name of an energy-economy simulation model developed and maintained by the Energy and Materials Research Group at Simon Fraser University, BC, Canada.

[4] Partial-equilibrium models simulate the supply-demand equilibrium of selected goods, ignoring adjustments in the rest of the economy.

results demonstrate that modelling regional energy supply and demand is an important and necessary component of climate policy analysis, especially for Canada.

This research will be of interest to those involved in energy and environment policy analysis in Canada and to researchers interested in using models to simulate the effects of policy designed to tackle environmental problems such as climate change.

Report outline

This chapter is an introduction to climate policy analysis and the requirements of models used to evaluate climate policy. I describe the CIMS model and explain why it is suitable for this task. I then explain the objectives of this research and how they contribute to wider ongoing efforts to improve climate policy analysis. Chapter 2 describes how I constructed energy demand models of the US and Canada. Chapter 3 describes the energy and emission characteristics of the models. Chapter 4 describes the energy trade model and supply models that I used to integrate the energy demand models. The policy scenarios are also described. In Chapter 5 I present and discuss the results of simulations using the integrated model. I also investigate how uncertainty in trade model parameters affects the results. In Chapter 6 I conclude by summarizing the outcome of the research, next steps and recommended future research. References and other information are provided in the final sections of the report.

Climate policy

Greenhouse gas emissions and other harmful air pollutants are produced in all sectors of the economy – industry, agriculture, commercial enterprise, transportation and households. They are by-products of the daily activities of millions of people utilising tens of thousands of technologies to fulfil human needs and desires. When activities have negative social impacts or externalities, governments may seek to modify behaviour or technology choice through public policy.[5] Regulations that penalise undesirable actions or reward desirable actions can change behaviours and purchasing decisions. Incentives or disincentives may be financial penalties or the threat of legal action.

[5] An externality is a cost or benefit that is not reflected in the price of a good or service.

As political pressure to avoid climate change increases, government decision makers look for policy solutions. Policy analysts provide information to decision-makers to help them evaluate policy alternatives and to design policy. Policies are usually evaluated using the following four criteria or variants of them – political acceptability, effectiveness, efficiency, and administrative feasibility.

The political acceptability of a policy is the likelihood that it will have enough political support to be implemented. That depends on its perceived impacts on the general public and on elements of society that are represented in the political process. Lobbyists or interest groups that represent specific elements of society such as industries, environmental causes, disadvantaged or minority groups, participate in the political process and determine the political acceptability of policy proposals.

For example, if policy-makers are considering a tax on emissions, then representatives of industry want to know how much the costs of production will increase because this will affect competitiveness. If producers go out of business or have to cut costs, then there may be job losses or plant closures, something that politicians want to avoid. The general public usually wants to know how much fuel prices and household energy bills will increase and the government may be concerned about the impact on future economic growth. By better understanding what the many and diverse impacts might be, and by estimating their magnitude, policy analysts can improve the policy-making process.

The extent to which climate policies are effective in reducing or avoiding future emissions, depends on their ability to change behaviours and purchasing decisions. Because of political opposition (or a lack of political support) governments in Canada have until recently shied away from compulsory policies and policies that involve financial penalties (Jaccard et al., 2004). Instead they favoured voluntary policies that provided information or used moral suasion to influence behaviour, and subsidies that reward desired behaviour. These policies have proved to be largely ineffective as emissions have continued to increase in line with economic growth. The available research indicates that compulsory policies or policies that incorporate significant financial disincentives are more effective than voluntary policies or modest subsidies (OECD, 2003).

As well as effectiveness in achieving an environmental goal, a policy may be evaluated on its economic efficiency. To minimise the overall cost to society, a climate policy should stimulate the adoption of only the lowest cost technologies or behaviours from all sectors of the economy necessary to achieve the goal. One way to measure the relative cost of emission abatement opportunities is to consider the cost per unit of emissions avoided, also known as the abatement cost. For greenhouse gas emissions, this is commonly expressed in units of dollars per metric tonne of carbon dioxide equivalent (CO_2e) avoided.[6] In theory, and assuming the costs of all opportunities are known, making all emitters in the economy pay an equal price for their emissions will ensure that all opportunities equal to or less than the price of emissions will be exploited. The theory is that firms and households take account of the cost of current and future emissions when making purchasing and investment decisions and modify their decisions accordingly.

Finally, administrative feasibility may also be a consideration in evaluating policy options. A policy that is difficult to implement and administer may cause additional costs to government and society that reduce its economic efficiency or political acceptability.

Policy mechanisms

When it comes to policies that put a price on emissions, two policy mechanisms currently dominate. One is the carbon tax and the other is the emission cap and permit trading system. A carbon tax is a Pigouvian tax applied to each unit of greenhouse gas emitted by firms and households.[7] The government sets the level of the tax and may adjust the level over time.

[6] Carbon dioxide equivalent or CO_2e is a common measure of the global warming potential of all known greenhouse gases.

[7] A Pigouvian tax is a tax levied to correct the negative externalities of a market activity. Named after Arthur Pigou (1877-1959).

A cap-and-trade system is an alternative to a tax. Rather than setting the price of emissions, the government sets a limit on the total amount of emissions permissible in a given sector or sectors of the economy. Firms are allocated permits to emit (freely or by auction) and a market is established in which firms can trade permits. The emission price is determined by the price of permits in the market. The debate on which mechanism is most suitable for climate policy hinges mainly on the relative importance of the aforementioned policy evaluation criteria – effectiveness, efficiency, political acceptability and administrative feasibility (Weitzman, 1974).

One possible modification to the cap-and-trade system is an upper limit on the market price of emission permits, known as a *safety valve*. The purpose of this modification is to avoid severe economic impacts in the event that achieving the absolute emission target proves more costly than anticipated. The limit can be set low at first and then raised later to give producers and consumers more certainty about the likely costs of emissions. If the emission price reaches the limit the government sells unlimited additional permits at the maximum price. This undermines the environmental objective but limits the price of permits. When this happens the system behaves exactly like an emission tax (Jacoby and Ellerman, 2004).

Despite the differences between a tax and a cap-and-trade system, they serve the same purpose – to ensure that emitting has a price. Therefore, either policy mechanism, including cap-and-trade with a safety valve, may be simulated in an energy-economy model by a price on emissions, without the need to simulate the specific policy mechanism itself. However, the impact of a carbon tax or a cap and trade system is not limited to the price on emissions. With a carbon tax, a redistribution of income occurs between the emitters who pay the tax and the final recipients of the tax revenue raised by the government. The tax revenue may be redistributed in a variety of ways. The revenue may be returned to the economy in the form of reductions in other taxes such as income tax or corporate profit tax. Alternatively, some or all the revenue from the carbon tax may be spent on programs to assist firms and consumers in reducing their emissions, or on the development or demonstration of alternative technologies. With a cap and trade system, trade in permits results in transfers between emitters and those who reduce emissions. Determining who benefits from the redistribution and the degree to which a policy is perceived to be revenue-neutral from the government's perspective, is an important factor in evaluating political acceptability.

When evaluating policies it is also necessary to understand how the emission price is conveyed to final consumers in practice. In a cap-and-trade system the majority of small emitters – small businesses and households – are not required to trade in emission permits directly. This would not be administratively feasible and the cost of measuring emissions from a large number of point sources is high. Instead, fuel suppliers are required to acquire permits on behalf of final consumers to cover end-use emissions from fuel-use. This is possible because greenhouse gas emissions from fuel combustion are proportional to the carbon content of fuels, which is known. Likewise in a tax system, the emission tax is collected by fuel suppliers from final consumers at the point of purchase as a fuel tax. In both cases the price of fuels experienced by final consumers includes the emission charges from both production and final consumption of the fuels.

In addition to the carbon tax and cap-and-trade system, other market-oriented regulations are available that target specific sectors such as the renewable portfolio standard for electricity generation (Berry and Jaccard, 2001), as well as a raft of *command-and-control* regulations that target the efficiency of specific technologies, such as household appliances and vehicles.

Importance of models

Estimating the cost and effectiveness of climate policies is difficult because (1) there is uncertainty in the costs and benefits of technologies, especially in future costs and benefits; (2) modelling human behaviour and decision-making is difficult and (3) the economic effects of environmental policies can be diverse and widespread.

Computer models are useful for analysing complex real-world problems because they provide a simplified (usually mathematical) approximation of the real world that may be used as a substitute for real-world experiments. However, reliably predicting the effects of climate policies requires a realistic model of the entire economy, including human behaviour. Nevertheless, policy decisions need to be made and policies designed, so analysts develop models and apply them to environmental problems such as climate change in the hope of improving the policy-making process. There is considerable uncertainty in model results, but the use of models has, at a bare minimum, led to a better understanding of the problem of policy evaluation and of the probable effects of climate policy choices.

Model requirements

Box 1 summarizes the requirements of simulation models for climate policy analysis. First and foremost, models must at some level of detail describe the energy and emission characteristics of economic activity. Whether it is down to the level of individual technologies used by households and firms or simply in terms of economic output, models must describe how economic activity consumes energy and produces emissions through the use of technology.

The energy and emission characteristics of economic activity change over time, and models must account for this. The rate of change is governed by three processes, the development of technology with different characteristics, the depreciation and retirement of existing capital stock, and the decision-making behaviour of producers and consumers who purchase and use technology according to their preferences. The later is probably one of the hardest processes to model because human behaviour and decision-making is complex and heterogeneous, and future preferences are hard to anticipate.

Box 1. Requirements of climate policy simulation models

- Energy, emission and cost characteristics of technologies
- Technological progress
- Capital stock turnover
- Producer and consumer decision-making behaviour (preferences)
- Learning-by-doing and induced technological change
- Response of energy demand to prices
- Energy supply (including imports and exports)
- Economic re-structuring (trade and investment)
- National income and economic growth
- Government expenditure
- Other impacts

Simulating technological change is an important requirement of models. New and improved technologies are created as a result of the processes of invention and innovation. The cost and performance of a technology also tends to improve during its application. This is not only due to normal economies-of-scale but due to a learning-by-doing effect whereby know-how increases and technologies are perfected as a consequence of experience gained during production and use (Löschel, 2002). The phenomenon is particularly important for new technologies in the early stages of their lifecycle. Some policies are specifically designed to induce technological progress by increasing production of selected technologies or by increasing research and development activity. Models could benefit from an endogenous treatment of technological progress that simulates the effects of learning-by-doing and induced technological change (Jaffe et al., 2002).[8]

Supply and demand

Next on the list of model requirements is the need to account for changes in energy supply and demand. Changes in technologies cause changes in energy use. Changes in energy demand require a change in supply and there may be an adjustment in the price of energy as well. Any change in energy price has a ripple effect throughout the economy, changing investment and purchasing decisions in all sectors. When the prices of goods and services change, consumers adjust their consumption.

Energy prices are a result of complex market forces on the demand and the supply side. For this reason energy price forecasts are uncertain, even in the short run. To investigate this uncertainty, I compared energy price scenarios produced by the Energy Information Administration for the Annual Energy Outlook (AEO) in the last seven years. The AEO is the most comprehensive forecast of energy supply and demand available for the US. Figure 1 shows the reference case natural gas price scenarios issued each year since 2001. Also shown is the actual historic price.

Price forecasts are revised each year as economic conditions change and new information becomes available. The natural gas price forecast was increased each year to

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[8] Endogenous means internally derived by the model.

reflect unanticipated short-run increases. The long run price forecast also gradually increased from around 4 dollars per gigajoule in the forecasts before 2003 to 6 dollars in the recent forecasts. Because of uncertainty it is important to consider alternative price scenarios when simulating climate policy.

Figure 1. Reference case scenarios of natural gas price.

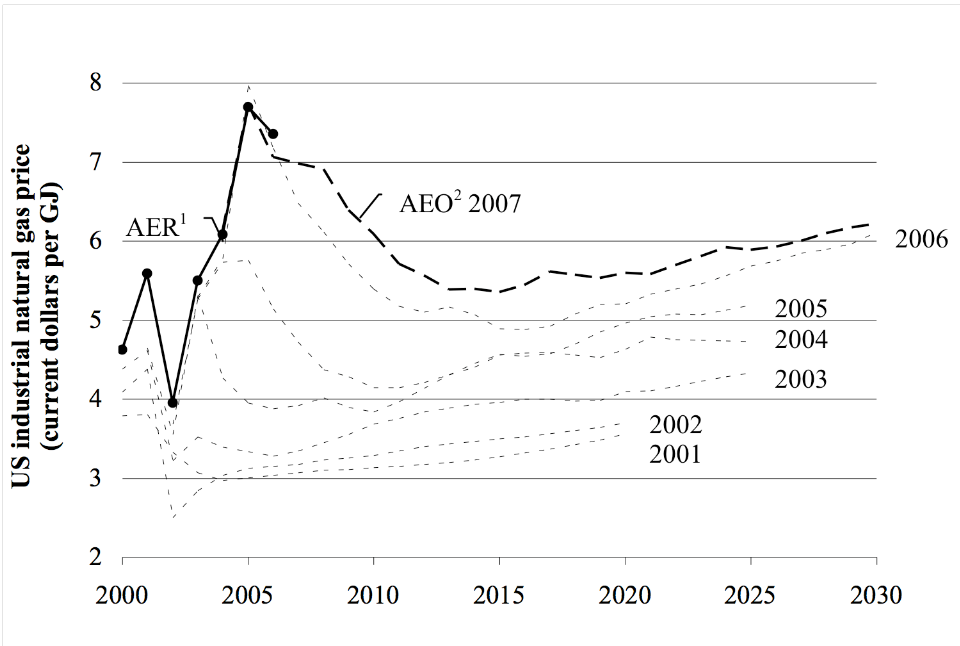


Figure notes:
1. Historic price from the Annual Energy Review (EIA, 2006).
2. Annual Energy Outlook 2001 to 2007 (EIA, 2006).

Any change in energy demand must be matched by a corresponding change in supply. This could be a change in domestic production or a change in imports and exports, or a combination of both. Modelling energy supply is important because changes in domestic production may significantly increase or decrease emissions and thus contribute to the outcome of the policy. To simulate energy supply and demand a model must find a set of conditions where supply, demand and price are in equilibrium. A model that finds equilibrium conditions in just one or a few markets is referred to as a partial-equilibrium model.

When energy and emission prices change, other adjustments occur in the economy. If production costs in industrial and manufacturing sectors increase, marginal producers who compete in international markets may go out of business or reduce output. Output in other sectors could increase. The result is a structural change in the economy, such as a decline in heavy industry and a growth in service industries.

In competitive markets, prices of traded goods and services may change. The degree to which domestic prices change depends on the degree of international trade and the nature of the global market. Changes in commodity prices may have a further ripple effect on production, consumption and international trade. Modelling these changes requires a detailed input-output model of the economy that can track production and consumption of all goods and services by all sectors, as well as imports and exports.

Macroeconomic response

When widespread or large adjustments occur in prices, it may be necessary to simulate the entire economy. Models that simulate adjustments in all markets – not only the markets for goods and services but also investment and labour markets – are known as computable general equilibrium (CGE) models. CGE models represent production, consumption, trade, investment, labour, and government expenditure with equations that simulate their behaviour in response to prices. When energy prices increase, total expenditure on energy usually increases and this has an impact on total income, consumption, savings and investment. Including government expenditure in a model may be necessary when simulating policies that generate additional tax revenue that is re-distributed in the economy. By taking all economic impacts into account a CGE model can estimate the adjustment in overall economic growth as a result of a policy. Forecasts of future emissions can then be adjusted to account for expected changes in economic growth.

The impact of macroeconomic effects may or may not be significant. It depends on the policy and the nature of the economy. However, to verify the likely impact or to convince policy-makers of the size of the impact, it may be necessary to include a macroeconomic model. Models that simulate the macro-economy also provide useful information on other economic impacts of policies, such as changes to wages and employment, income redistribution and estimates of welfare costs.

A macroeconomic model of the economy of one country or region may not be adequate for climate policy analysis. Most national economies are not closed. They are connected to the economies of neighbouring countries and to global markets for goods and services, capital and labour. Simulating the economy of one region involves making assumptions about global markets and the rest-of-the world and how they may respond to changes in the economy that is modelled. These assumptions include an assumption about what policies may be adopted in other regions during the simulation period. With different countries taking different approaches to addressing climate change, models that simulate different regions of the world and global markets are required. Multi-region models are also useful for investigating effects on international trade and investment that may occur as a result of climate policy.

The CIMS model

CIMS is a technologically explicit model. It contains a detailed representation of energy technologies used in all sectors of the Canadian economy. Technologies in each sector are organised in a hierarchy of energy services called an energy *flow model*.[9] The flow models define how output from each sector is produced by a set of processes and activities that demand energy services, such as mechanical power, heating, cooling and lighting. Each energy service is in turn delivered by energy technologies, such as electric motors, furnaces and light bulbs. In total, the fifteen sector models contain over 1,500 technologies. Many are specific to the unique uses of energy in each sector.

In each node of the flow model there is a set of technologies.[10] The available technologies provide the opportunity for technological progress and the possibility of substitution between different technologies. One version of a technology reflects the current capital stock in use at the beginning of the model simulation. The others represent

[9] Appendix C contains diagrams of the energy flow models of the US-CIMS model.
[10] Nodes are represented as boxes in the flow model diagrams.

alternatives and improved versions of the technology that are available in current and future years.

Each technology has a defined lifespan. The model simulates the evolution of technologies in 5-year increments. From one time period to the next, a proportion of the stock of technologies in use is retired. The loss of retired stock and the requirement for new stock to meet growth in demand is provided by new technologies from the set of available technologies. Determining the share of new demand that is provided by each technology is where the behavioural simulation capabilities of CIMS come into effect. The share of each new technology is determined by its lifecycle cost. The lifecycle cost is an estimate of the total cost of a technology and includes upfront capital cost, operating, maintenance and energy costs. For the purposes of comparing technologies, capital costs are converted to an annual amount that is spread over the technology's life.

Rather than assume that all decision-makers choose the same technology (the optimum technology with the lowest lifecycle cost), the CIMS model uses a market share function to determine how much of each technology is adopted (Bataille, 2005). The function is calibrated in each instance to reflect the influence of lifecycle costs on technology choice. The market share function is a way of simulating real-world preferences and decision-making behaviour, which is heterogeneous and may be based on multiple factors and constraints other than costs. Costs also tend to be heterogeneous from one application to another.

The behavioural realism of the decision-making model is further improved by estimates of intangible costs that are included in the lifecycle costs of some technologies. Intangible costs are non-financial costs that reflect real disadvantages or risks associated with technologies. For example, an alternative technology may not be a perfect substitute for a conventional technology. A new innovation may have risks associated with it due to a lack of production experience. CIMS is able to simulate intangible costs that decline as market share increases and experience is gained.

CIMS simulates policies that put a price on emissions by including the emission costs in the lifecycle cost calculation. Because CIMS has a detailed representation of the characteristics of energy technologies and a behaviourally realistic simulation of decision-making, it is also useful for simulating the wide variety of policies that are designed to induce technological change. Minimum or maximum constraints on the market share function are used to simulate technology standards. Subsidies or financial penalties can be simulated using adjustments to the lifecycle cost of technologies.

By simulating the behaviour of consumers and producers, the sector flow models also simulate the relationship between energy demand and prices. Changes in energy prices change the lifecycle costs of a technology according to its energy use characteristics. When the lifecycle costs of technologies change, they gain different levels of market share and the capital stock evolves in a different way. The adjustment in the stock of technologies changes total demand for each type of energy.

Because energy prices are uncertain, CIMS uses exogenous energy price scenarios (inputs to the model that are not determined by the model) and simulates how prices may diverge from these scenarios. CIMS does not attempt to simulate short-run fluctuations in price that result from short-run adjustments to supply or demand. The model forecasts changes in the price of energy that result from long-run changes in supply and demand.

Limitations of CIMS

As described above, CIMS simulates the response of energy demand to changes in prices in its detailed sector models. On the supply side, the cost of energy production is also affected by alternative energy prices. For example, the cost of electricity generation depends on the prices of coal and natural gas. CIMS calculates changes in the costs of technologies used in the production, conversion and transportation of energy and uses these to estimate an adjustment to supply price. To do this requires various assumptions to be made about energy supply and about energy markets. Because of these assumptions the current version of the model is less suitable for simulating larger regions and trade between regions.

In the current version of the CIMS-Canada model, changes in energy trade are simulated in each region of the model independently. The assumption is that net exports of an energy commodity by a region change only in proportion to the change in the average cost of production in that region. Equation 1 describes how this adjustment is made. Adjusted production X in each region is the sum of production in the business-as-usual scenario X_{BAU} and an amount that reflects an increase or decrease in net exports.

$$X = X_{BAU} + NX_{BAU}\sigma\frac{P}{P_{BAU}}$$ **Equation 1**

NX_{BAU} is net exports (exports minus imports) in the business-as-usual scenario. σ is a price elasticity of net exports, that translates the change in the domestic cost of production into an adjustment in net exports. P_{BAU} is the cost of production in the business-as-usual scenario and P is the cost in the policy scenario. The change in the cost of production in the policy scenario is estimated from the change in the average financial lifecycle cost of production $FLCC$ as follows.

$$\frac{P}{P_{BAU}} = \left(\frac{FLCC}{FLCC_{BAU}} - 1\right)COP \qquad 0 \le COP \le 1$$ **Equation 2**

$FLCC$ is calculated by the energy supply sector flow models. It is the sum of the lifecycle costs of all energy technologies in a sector divided by total output in a given time period (Bataille, 2005). In other words it is the average cost of production of one unit of output. Lifecycle costs include annualised capital costs, operating and maintenance costs, energy costs and emission charges of all technologies included in the flow model. The constant COP defines the proportion of the total cost of production that is included in the flow models. This varies from one sector to another.

The suitability of this method of simulating energy trade adjustments in the current seven-region model of Canada depends on estimates of the demand-elasticity of net exports σ. The values of σ used in the model were taken from an econometric survey and are in the range -0.9 to -0.5 (Bataille, 2005).

One problem with the current model is that it cannot simulate two-way trade in the same commodity. Because the model can only simulate changes to net exports it can only simulate regions or countries where trade is predominantly either imports or exports. Small regions do not usually import and export the same energy product, but if the model is to be used to represent larger aggregate regions (countries or groups of countries) then a new model of energy trade is required that can simulate imports and exports by one region. To simulate trade in goods other than energy, a bi-directional trade model is essential.

The second problem with the current energy trade model is that it does not balance supply and demand in all regions. Adjustments to imports or exports are determined only by the local cost of production in each region. In reality trade depends on the cost of production in other regions and on demand in all regions. Total supply and demand must be in balance.

Thirdly, the current model has computational limitations. It does not have a robust solver algorithm that is able to solve complex energy supply and demand interactions. Because of this it has proved difficult to run simulations when more than one or two energy prices are endogenous. Usually only the price of electricity is determined endogenously and so only adjustments to electricity trade are simulated. This is a limitation because changes in the price of other fuels, such as refined petroleum products, natural gas and crude oil, could have important impacts on supply and demand and therefore should be included.

Finally, the current model does not allow changes in the consumption of energy in energy supply sectors other than electricity generation to be reflected in total demand.[11] Assuming that changes in energy use in primary energy sectors do not affect total energy demand simplifies the model and makes computation easier. The omission is usually not a big issue because the proportion of energy used by supply sectors is not a large proportion of total demand and does not change much. However, this is not always the case, especially in Canada where the escalating demand for energy for unconventional oil and gas production could have an important impact on energy supply and demand

[11] Energy use by primary energy sectors is sometimes referred to as *producer consumption*.

(Söderbergh, 2007). For this reason I wanted to include energy consumption by primary energy supply sectors in my model of energy demand.

These limitations in the way that energy supply is simulated in CIMS and the desire to model larger regions and trade between regions are the main motivations behind this research.

There is no trade model for goods other than energy products in CIMS. Instead, the model simulates how domestic manufacturing output might adjust to changes in the domestic cost of production in each sector as a result of climate policy. The approach is similar to the way energy trade adjustments are modelled except that the elasticity is applied to sector output rather than net exports. The elasticity of output simulates the combined effect of changes in trade and domestic consumption as a result of a change in the domestic cost of production.

Finally, CIMS does not have a complete model of household consumption or the macro-economy. Instead it simulates the possible effects of changes in consumption and the macro-economy using an own-price elasticity of demand in final consumption sectors. An elasticity of personal transportation demand adjusts the demand for personal transportation according to the cost of personal transportation, likewise for residential energy use. There are methods of simulating the redistribution of government revenue from a carbon tax policy in CIMS but I have not used them in this research.

Justification for a US-Canada model

In this section I explain why an integrated model of the US-Canada energy system is important for Canadian climate policy analysis. Because of Canada's geographic layout and proximity to the US, its economy is deeply integrated with that of the US. A history of co-operation between Canada and the US culminating in trade agreements in the late '80s and early '90s, allowed Canada to benefit from increased trade and investment.[12] The Canadian economy is now more closely integrated with the United States than at any time in history. It is about one tenth the size of the US economy and the level of

[12] The Canada-U.S. Free Trade Agreement (CUFTA) and the North American Free Trade Agreement (NAFTA) were signed in 1988 and 1994.

integration means that it is more affected by changes in the US economy than other countries. To put this into perspective, around 80 percent of Canada's exports are to the US and 65 percent of its imports are from the US (Beaulieu and Emery, 2006).

Not only is Canada's international trade dominated by trade with the US, Canada's economy is more dependent on international trade than other countries. A country's trade dependence may be defined as imports and exports as a proportion of gross domestic product (GDP). Table 1 shows both these indicators for four countries including the US and Canada.

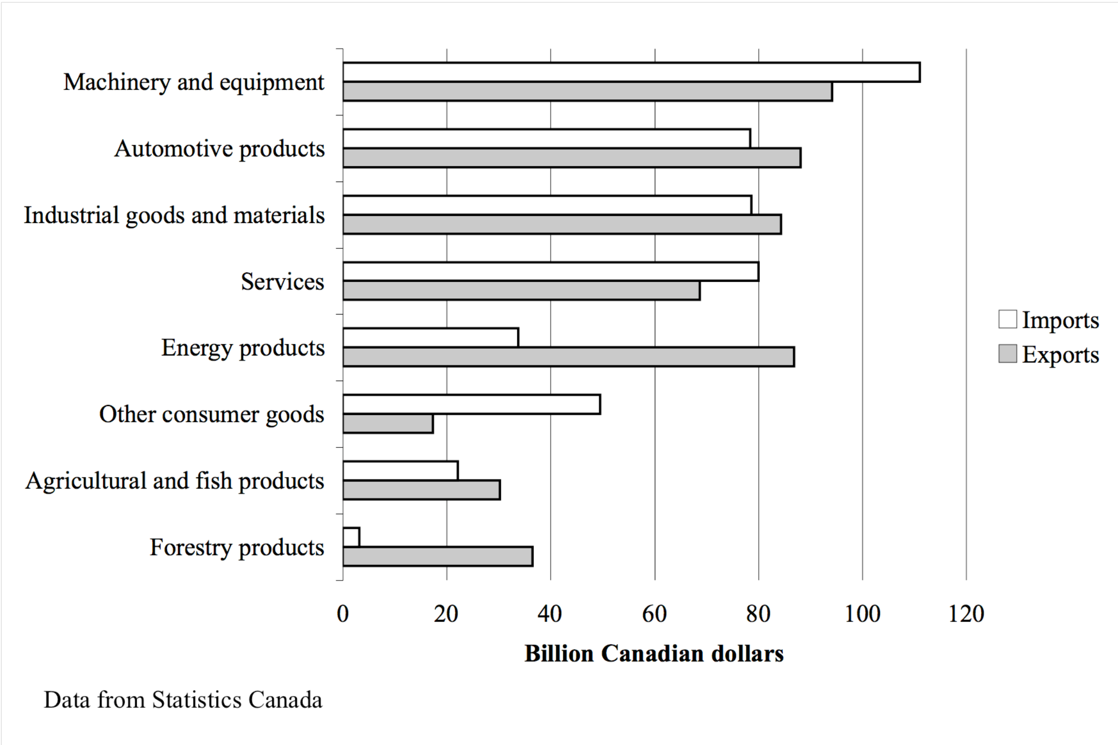
Table 1. Canada's trade dependence

Country	**Exports as a percent of GDP in 2005**	**Imports as a percent of GDP in 2005**
Canada	38	34
Mexico	30	31
UK	26	31
US	11	16

Data source:
TABLE 4-1, pp. 23, Government of Canada, (2007).

Canada is more dependent on trade than other developed countries, especially on exports. Figure 2 shows imports and exports by Canada in 2005. Canada is a net exporter of commodities, particularly energy and forestry products and depends on these exports for its trade surplus (Uddin, 2006). The fact that the commodity sector plays such an important role in Canada's economic prosperity is an important issue for climate policy-making because commodity sectors tend to be energy and emission-intensive and thus vulnerable to cost increases as a result of climate policy. Canada's specialization in commodities makes its economy vulnerable to changes in commodity prices as well as changes in the domestic cost of production that result from climate policy.

Figure 2. Canada's imports and exports in 2005.



Reductions in greenhouse gas emissions are a collective public good because all countries benefit by avoiding future damages from climate change, regardless of where abatement actions occur. However, the costs of reducing greenhouse gas emissions are lower when they are distributed widely, so there is an incentive for countries to co-operate and to co-ordinate climate policy. The US-Canada model is a useful tool to analyse the benefits of climate policy co-ordination between Canada the US.

Research objectives

The main objective of this research is to improve the analysis of Canadian and US climate policy by building a simulation model of the combined energy supply and demand system of both countries. The aim is to overcome the limitations in the way that energy trade is simulated in the existing CIMS model and to make progress towards a model that meets all the requirements of energy-environment simulation models outlined earlier in this chapter. The project involved the following four major tasks.

1. Build realistic simulation models of US and Canadian energy use that forecast future energy use and emissions by simulating the evolution of the capital stock

under the influence of alternative energy prices and energy-environment policies.[13]

2. Connect these energy demand models to energy supply models using a model of international energy trade, and simulate energy supply and demand equilibrium in the integrated system.
3. Use the integrated energy-economy model to simulate different scenarios of future US and Canadian climate policy and investigate possible adjustments to energy supply and demand that result from the policies.
4. Consider how uncertainty in the model may affect the results.

Although the project is motivated by the immediate opportunity to improve the analysis of Canadian and US climate policy, the overall aim is to advance energy-environment modelling capabilities so that other regions can be included, and ultimately so that global climate policy scenarios can be evaluated.

[13] I use the term energy-environment policies here because the model must be able to simulate a wide range of energy-related environmental policies as well as those described earlier in this chapter. These are a sub-set of possible energy-environment policies.

CHAPTER 2: METHOD

I used an existing CIMS model of Canada as the starting point to build two new models of Canada and the US. The existing model of Canada is divided into seven regions that represent the six most populated provinces in Canada – Ontario, Quebec, British Columbia, Alberta, Saskatchewan, Manitoba, and a region called Atlantic that represents the smaller east coast provinces. The seven-region model is used for analysis of national and provincial environmental policy in Canada. The regional disaggregation into eighty-four independent sector models allows variation in climate, geography, preferences, policy, resources and technologies to be adequately represented, as well as some energy trade between provinces.[14]

Regional disaggregation requires more data and computational resources. I decided that one-region models of the US and Canada are more suitable for this research project. As well as saving computational resources, geographically aggregate models are less complex and therefore easier to comprehend and maintain. There is less scope for error and analysis of simulation results is less time consuming. Building models that represent larger regions is also consistent with the research goal of simulating global climate policy.

Canada model construction

An "aggregation process" was used to produce a one-region Canada model. The components of the one-region model are in most cases a sum or an average of components in each region of the seven-region model. For example, the forecasted number of residential households is the sum of the forecasted number of households in each region of the seven-region model. The price of a ton of coal in the electricity sector of the one-region model is an average of the coal prices in the electricity sector models of

[14] Each region model in the existing Canada model contains a residential, commercial, transportation, and electricity generation sector model and a selection of industrial sub-sector models.

each region model. For some components of the model I used data from a representative region of the seven-region model. In any case, countless assumptions, approximations and estimates were made in order to produce the aggregate model.

I encountered numerous functional problems with components of the existing CIMS model and opportunities to improve the model and the data. Many of these I did not address. My goal was to produce a working one-region model in a short space of time. To validate the aggregation process I compared simulation results produced by the one-region model with aggregate outputs of the original seven-region model. Appendix E contains a list of model improvements that could be addressed when further research effort is available. Significant improvements were made to the seven-region Canada model after I started construction of the one-region model. It would not take a great deal of effort to translate these modifications to the one-region model. If the one-region model is required for future research, then consideration should be given to how it could be maintained.

US model construction

I used the one-region model of Canada as the starting point for the construction of the US model. I began by adjusting total demand in each sector to US data and then I modified energy service demands, energy prices and technologies until energy use and emissions matched US historic data in the year 2000. All prices and cost information in the US model is in US dollars in the year 2000. I used exchange rates in the year 2000 and consumer price indices to convert data from other sources.[15] Unless otherwise stated, all cost information in this report is in US dollars in 2000.

In most cases the existing structure of the Canada sector models was suitable for the US models; however there were cases where deviating from the Canada model was the best approach. One was the US chemical sector model, which required a complete redesign. Diagrams of all the energy flow models of the US model are included in Appendix C.

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[15] The US-Canada exchange rate in 2000 was 1.49. Cost data in the Canada model is in Canadian dollars in 1995.

Most data I needed for the US model were publicly available from the Energy Information Administration (EIA, 2006) or were derived from input data files from the National Energy Modelling System (NEMS).[16] In some sectors such as transportation, data from other government agencies were used. The non-energy industrial sector models were built with the help of J. Roop of the Pacific Northwest National Laboratory, who provided data and expertise on US industrial energy use.[17] Final adjustment of the model to match US energy use and emissions was achieved by modifying technology coefficients.

The results of the model calibration process are shown in Table 2 where data from the CIMS-US model in the year 2000 are compared to historic data on energy use and emissions. Consumption of natural gas and refined petroleum products in the CIMS-US model are significantly less than the reference data and total greenhouse gas emissions are 10 percent less than the reference. The variance is different for each fuel and the reasons for the remaining variance are complex. Table 18 in Appendix A shows the detailed calibration results for each sector model. The variance in natural gas use occurs in the industrial sector. However, consumption in the industrial sector models in CIMS calibrates well with the reference data. Not all energy consumption categorized as industrial by the EIA is accounted for in CIMS. For example, CIMS does not have a model of the construction sector.

[16] The National Energy Modelling System is the primary model used by the US Department of Energy to produce national forecasts of energy demand and supply (EIA, 2006).

[17] J. Roop is an expert on the economics of industrial energy use. The Pacific Northwest National Laboratory is operated for the US Department of Energy by Battelle Memorial Institute.

Table 2. Year 2000 calibration results for the US model.

Source	Energy consumption (petajoules)					Greenhouse gas emissions (million metric tonnes CO_2e)
	Electricity	Natural gas[2]	Refined petroleum products[3]	Coal	Other fuels[4]	
Reference data[1]	12,381	28,267	35,737	23,053	4,569	6,493
Model data	12,191	24,167	32,636	22,591	4,347	5,839
Variance	-189	-4,101	-3,101	-462	-222	-654
Percent of reference	-2	-15	-9	-2	-5	-10

Table Notes:

1. Reference energy consumption data from the Annual Energy Review 2004 (EIA, 2005). Reference greenhouse gas emissions from the US Greenhouse Gas Emission Inventory, (EIA, 2006).
2. Includes propane (liquefied petroleum gas).
3. Excludes propane (liquefied petroleum gas).
4. Includes by-product gases and liquid fuels such as still gas and black liquor.

CHAPTER 3: SECTOR MODEL CHARACTERISTICS

In this section of the report, I describe key features of the energy flow models of each sector of the economy. My aim is to provide insight into the dynamics that determine the behaviour of the models and to what is and what is not included in the models. I also provide quantitative model characteristics that other researchers may compare to other models or to real-world observations.

In order to interpret simulation results, it is necessary to understand individual sector model because together they determine overall results. First I ran simulations to characterize the behaviour of individual sector models. I analysed the business-as-usual scenario and a climate policy scenario to produce a set of indicators that reveal sector model characteristics, such as the sensitivity of energy demand to changes in prices. If the price of an energy commodity is increased compared to the reference scenario then the costs of some technologies are higher and the market share captured by each technology is different. Similarly, when emissions are priced, the costs of some technologies increase and the technology stock evolves on a different path. To investigate these effects, I ran simulations of all sectors independently with variations in an energy price or the emission price while holding sector output and all other prices fixed at reference levels. For each simulation, I looked at changes in future energy demand and greenhouse gas emissions compared to the reference scenario (business-as-usual). This analysis revealed which sectors experience the biggest changes in energy demand and emissions.

To simplify the results, I group the fifteen sector models into four aggregate economic sectors. The residential, commercial and institutional sector includes all end-uses of energy in buildings. The transportation sector includes all road, rail, marine and air transportation of both people and freight. I group all industry sectors including petroleum refining, natural gas production, oil production and coal mining. Electricity generation is a separate category because of its significance in the US in terms of emissions, energy consumption and energy costs. This categorisation is consistent with Energy Information Administration reports on energy use (EIA, 2006).

Business-as-usual scenario

Before reviewing the results of alternative scenarios I describe the business-as-usual scenario and the results of business-as-usual simulations. The business-as-usual scenario is important because it is the reference point for alternative scenarios in which energy prices, demand, and supply, deviate from business-as-usual.

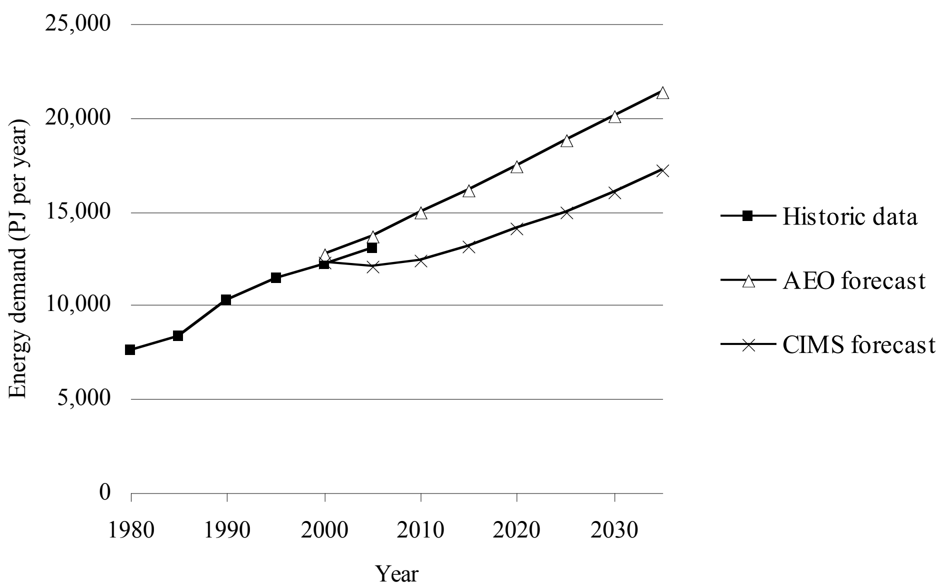
The business-as-usual scenario is determined by economic data from sources exogenous to the model. For the US model, I used the reference case scenario of sector output and energy prices from the EIA's Annual Energy Outlook 2006 (EIA, 2006). The Canada model is based on forecasts from a number of sources, including Statistics Canada, Natural Resources Canada, Environment Canada, and the National Energy Board (NEB, 2003). The Annual Energy Outlook (AEO) for the US is produced by analysts in the EIA who study worldwide energy supply and demand. Nevertheless, economic forecasts are uncertain and change from year to year as new information becomes available. The forecasts used in this research have already been superseded at the time of writing.

The AEO reference case is only one of a set of scenarios described by the EIA every year. Other scenarios could be equally likely predictions of the future. However, the set up time involved in modelling alternative scenarios prohibited consideration of any scenarios other than the AEO reference case. Future research could consider updating the forecasts and investigating alternative scenarios, such as a higher oil price scenario, to see how sensitive the results are to the reference scenario.

The assumptions about energy trade in Canadian forecasts were not the same as those in the EIA reference case. As an example, the Canadian forecast of natural gas exports to the US that I used is significantly higher than the EIA's forecast of natural gas imports from Canada. To produce a consistent forecast, I adjusted figures from both sources so that energy supply and demand are in balance in my reference scenario.

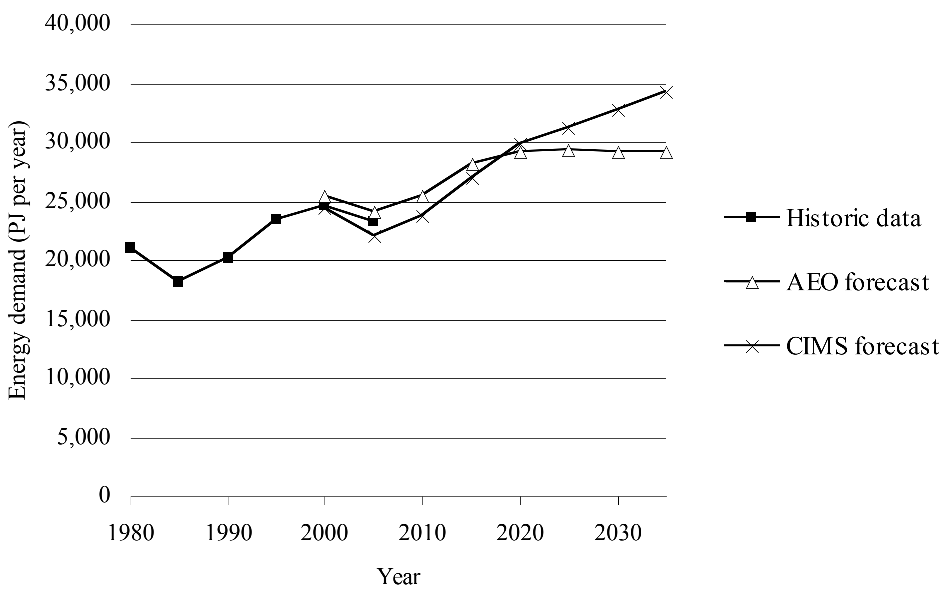
Simulating the business-as-usual scenario with the CIMS sector models produces a forecast of energy demand in each country. I compared these CIMS model forecasts to the EIA's reference case forecast in the Annual Energy Outlook (AEO). The three figures below show future electricity, natural gas and coal demand in the US and historic demand since 1980. For some energy commodities the difference between the EIA forecast and the CIMS model forecast is noteworthy. Electricity demand immediately departs from the historic trend in 2000 and declines. In contrast, the EIA forecast is a steady continuous growth in demand. In subsequent model time periods demand increases, and by 2035 it is growing at a rate of 1.4 percent that is similar to the EIA forecast.

Figure 3. Electricity demand – US



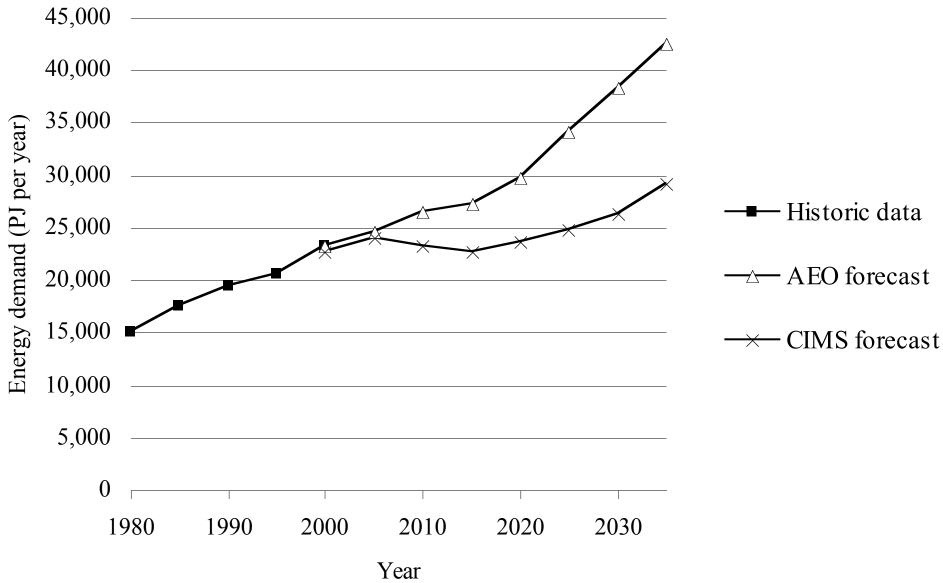
The difference raises questions about what is occurring in the CIMS model in the first model time period, from 2000 to 2005. Further investigation revealed that electricity demand is stable or declining in the commercial, residential, and other manufacturing sectors. As these sectors make up 80 percent of electricity demand they determine the trend. The stable or declining trend is the result of many technology choices in these models and is not limited to the US version of the model. I found that the version of the seven-region Canada model on which both my models are based also exhibited this trend. The issue should be investigated further as the historic data for 2005 show the forecast to be incorrect.

Figure 4. Natural gas demand – US



The forecasts for natural gas demand are almost identical initially but, in the AEO reference case, natural gas demand reaches a plateau in 2020 whereas, in the CIMS US model, it continues to grow. The CIMS US model forecasts a decline in coal use from 2005 to 2015 followed by slow growth thereafter, whereas in the AEO reference case, the forecast is for higher growth consistent with the historic trend initially, then increasing at a higher rate after 2020. I have not presented the graphs for refined petroleum products and crude oil. The model's forecasts for these are similar to the AEO reference case and also consistent with the historic trend.

Figure 5. Coal demand – US



Emission intensity

Emission intensity is a measure of the link between economic activity and emissions. It can be used to compare the climate impact of economic activity in different sectors or regions, or to quantify improvement in the climate impact of economic activity over time, independent of changes in economic output. It is useful to compare the rate of change of emission intensity over time with other models and empirical data because it determines the cost and timing of emission abatement.

Emission intensity is defined as the emissions associated with one unit of economic activity – such as the production or consumption of a good or service. However, the emissions associated with an economic activity may be defined in various ways, depending on the analysis. Direct emissions include the emissions from fuel combustion or other chemical reactions, and leaks of gases from equipment and machinery that are caused directly by the activity. Indirect emissions are emissions from other activities in the economy, that are in some way necessitated by the original activity, such as the emissions generated in the production of fuels and materials consumed by the activity.

When properly defined, emission intensity is a better measure of progress on reducing climate impacts than other measures such as energy efficiency or energy intensity (energy use per unit of output). Even so, it is common for policy analysis and policies to focus on the energy efficiency of technologies and the energy intensity of economic output. Emissions from energy production and use, especially from electricity generation, are a major source of emissions, so reducing energy use usually reduces emissions overall. Because energy use is understood and measured, it has become a practical lever for policy and regulation. However, in general, energy use is not a good proxy for climate impact because it ignores the different emission intensities of energy commodities and the possibility of improvements in the emission intensity of energy production and use. For example, switching from a fossil fuel to a renewable source of energy reduces emissions, but does not necessarily improve energy efficiency. Switching from natural gas to electricity may not change the energy intensity of consumption, but it could lead to an increase or decrease in overall emissions, depending on emissions from electricity generation. Finally, emission control technologies such as carbon capture and storage can reduce emissions associated with fossil fuel production and use, without reducing energy consumption. In fact, they are likely to increase energy consumption.

For simplicity, this analysis of emission intensity includes only indirect emissions associated with domestic electricity generation, as well as direct emissions by an activity. This is an informative indicator of the overall climate impact of economic activity because it accounts for the main source of indirect emissions - electricity generation. Indirect emissions associated with fossil fuels are not as significant. Accounting for them is difficult because of emissions embodied in fuel imports. All other indirect emissions are beyond the scope of this research.

Table 3 shows emission intensity estimates for the four economic sectors of the US and Canada in 2010 and 2030 in the business-as-usual scenario. To produce aggregate estimates of emission intensity for a group of sectors, a common indicator of output is required. To aggregate industrial sectors, I converted output into the GDP value of shipments using representative product prices. I converted residential, commercial and institutional demand to common units of building floorspace. Transportation demand is aggregated by simply adding personal transportation demand in passenger-kilometres-travelled to freight demand in tonne-kilometres-travelled.

Table 3. Forecasted GHG emission intensity by economic sector in the business-as-usual scenario – US and Canada[1]

(a) US

Economic sector	**Units of output**	**Greenhouse gas emission intensity[1] (tonnes CO_2e per unit output)** 2010	2030
Residential, commercial and institutional	Square metre of floorspace	0.078	0.068
Transportation	1000 (passenger-kilometres + freight-tonne-kilometres)	0.10	0.10
Industry[2]	1000 dollars of shipments	0.66	0.61
Electricity generation	Gigajoule	0.19	0.17

(b) Canada

Economic sector	**Units of output**	**Greenhouse gas emission intensity[1] (tonnes CO_2e per unit output)** 2010	2030
Residential, commercial and institutional	Square metre of floorspace	0.043	0.035
Transportation	1000 (passenger-kilometres + freight-tonne-kilometres)	0.12	0.12
Industry[2]	1000 dollars of shipments	0.65	0.76
Electricity generation	Gigajoule	0.05	0.04

Table notes:
1. Greenhouse gas emission intensity, as defined here, is the emissions of greenhouse gases per unit of sector output, including indirect emissions from domestic electricity generation, as well as direct emissions from fuel combustion and industrial processes.
2. Industry includes the industrial sectors and natural gas production, crude oil production, petroleum refining and coal mining.

Comparing the emission intensities in the US and Canada, the residential, commercial and institutional sector in the US is nearly twice as emission intense as the Canadian residential, commercial and institutional sector. This is mainly due to the difference in the emission intensity of electricity generation in the US and Canada, which is also shown in the table. Electricity generation in the US produces 0.19 tonnes of CO_2e per gigajoule of electricity in 2010, over three times as many as it does in Canada.

The emission intensity of industrial output is almost the same in both countries in 2010. However, in the US it declines from 0.66 tonnes of CO_2e per thousand dollars of output in 2010 to 0.61 in 2030. In Canada it increases to 0.76 by 2030. Emission intensity usually declines over time because technological progress allows producers and consumers to reduce their energy costs by adopting more efficient technology. The increase in Canadian industry is mainly due to rapid growth in unconventional oil production in the business-as-usual scenario.

The emission intensity of transportation does not decline in the US in the business-as-usual scenario. The reason is that electricity use for plug-in hybrid vehicles increases indirect emissions and offsets gains in vehicle efficiency. The emission intensity of transportation is 20 percent higher in Canada. According to the model data, Canada has more emissions from off-road transportation, road freight, light-duty trucks and rail freight per unit of demand than the US does.

I compared the CIMS-US estimates of emission intensity in the business-as-usual scenario with the reference case scenario from the Energy Information Administration (EIA).[18] The CIMS model predicts a faster decline in emission intensity in the residential, commercial and institutional sector than in the EIA reference case. Transportation emission intensity declines in the EIA reference case by 0.4 percent a year to 0.09 tonnes of CO_2e per unit of demand in 2030. For industry the EIA forecast indicates a 1.8 percent annual decrease in emission intensity of output. In the CIMS model it is only 0.4 percent a year. The EIA forecast for the electricity generation sector shows a slight decline in

[18] The reference case tables in the Annual Energy Outlook (EIA, 2006) provide carbon dioxide emissions and output in each sector from which I calculated emission intensity after including indirect emissions from electricity generation. One problem with this comparison is that the EIA forecasts of industrial output may include price effects. I assume constant future commodity prices in my calculation.

emission intensity after 2010 but by 2030 it is at the same level as 2010. In contrast, the CIMS model forecasts a decline in emission intensity in electricity generation at an average rate of 0.4 percent a year. The relative proportions of coal, oil, gas, nuclear and renewable generation in 2030 in the CIMS-US model are similar to those in the EIA reference case. I suspect that the CIMS model differs from the EIA's model in its assumptions about the likely adoption of more efficient and less polluting coal technologies in the business-as-usual scenario. A more thorough analysis of the EIA model might provide further insight on this.

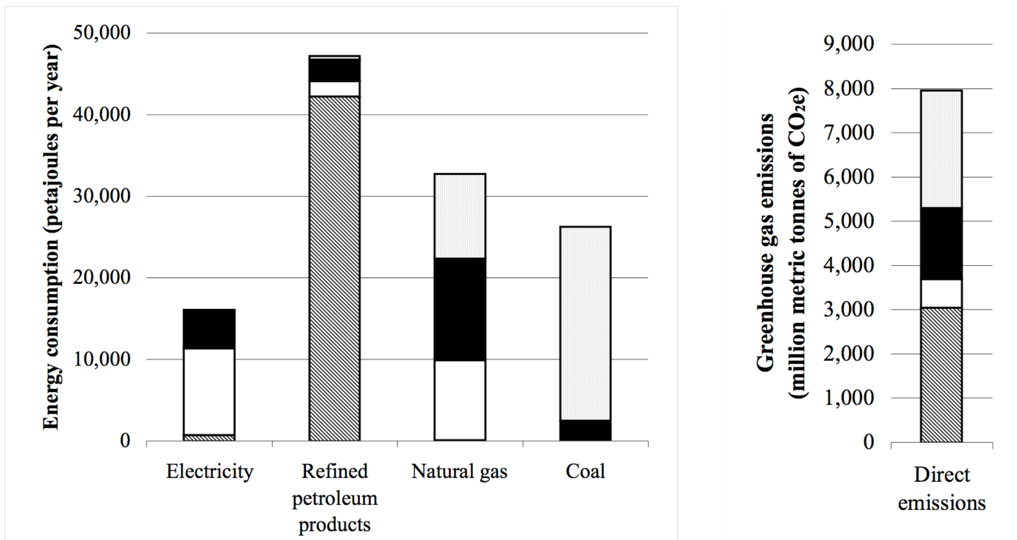
Future energy use and emissions

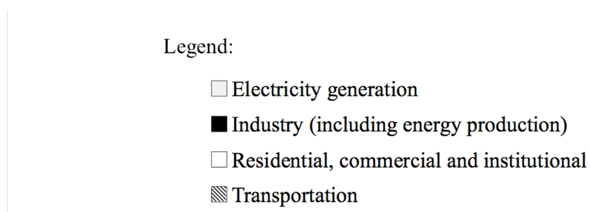
I use 2030 as a reference year for simulation results. The four graphs in Figure 6 show forecasted energy use and emissions in 2030 in the US and Canada in the business-as-usual scenario. The figures on the left show which sectors consume each of the four main energy commodities and the graphs on the right show each sector's contribution to total emissions. It is helpful to understand the differences in energy use between the two countries in order to interpret the results of policy simulations.

The countries differ significantly in the sources of emissions. The US transportation sector is responsible for 38 percent of total US emissions in 2030, more than any other sector. In Canada, the industrial sector, which includes energy production sectors except electricity generation, produces just over half of all emissions. The US electricity generation sector is the second biggest source of emissions. It is responsible for a third of US emissions. In Canada, the electricity generation sector is responsible for only 10 percent of total emissions. This is because Canada has a large amount of hydroelectric generation. Electricity generation in the US is still heavily dependent on coal in 2030 in the business-as-usual.

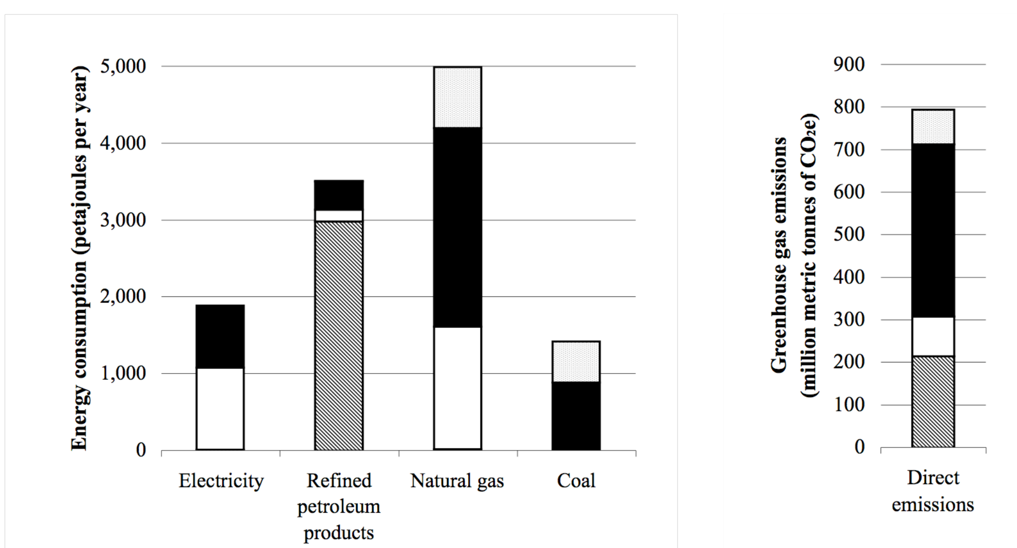
Figure 6. Forecasted energy use and emissions in 2030 – US and Canada

(a) Energy consumption in the US **(b) Emissions in the US**





(c) Energy consumption in Canada **(b) Emissions in Canada**



The industry sectors of both countries consume a large amount of natural gas, as well as electricity, coal and refined petroleum products. However, the industry sectors of the two countries are quite different. Industry in Canada consumes more energy and produces more greenhouse gas emissions per unit of economic output than industry in the US. This is mainly due to differences in the type of industry in the two countries. Canada has a high proportion of energy- and emission-intense commodity industries such as crude oil production, metal smelting and pulp and paper manufacturing. Crude oil production, especially from the energy and emission intense oil sands, is growing rapidly in Canada. In contrast, the US has a diverse manufacturing sector with a higher proportion of light manufacturing industries, such as consumer products and electronics. Crude oil production and some other heavy industries are in decline in the US. The CIMS model forecasts that in 2030 Canada's industry will produce 75 percent more direct emissions per unit of economic output than US industry.

In both countries the residential, commercial and institutional sector consumes a large proportion of electricity supply. The transportation sector consumes 85 to 90 percent of refined petroleum products (mostly gasoline). Natural gas is used widely in all sectors except transportation. In the US, 90 percent of coal supply is consumed by the electricity generation sector. Less coal is consumed in Canada and more is consumed by industry than by electricity generation.

In the next four sections of this report I describe characteristics of the CIMS sector models, key sources of data and the response of the models to changes in energy prices and the emission price.

Residential and commercial sector models

The residential and commercial sector models simulate energy use in residential, commercial and institutional buildings. The residential sector model represents single-family homes, multi-family homes and mobile homes. It accounts for energy used for space heating, air conditioning, lighting, cooking, clothes drying, refrigerators, other electrical devices, and the energy used to produce hot water.

The commercial sector model simulates energy use in a variety of commercial and institutional buildings including schools, universities, retail outlets, offices, hospitals, and warehouses. It accounts for energy consumed for space heating, ventilation, air-conditioning, lighting, hot water, cooking, refrigeration and other electrical devices.

In the US, the residential and commercial sectors are responsible for 38 percent of total energy use and 38 percent of the country's GHG emissions when indirect emissions are included. Electricity, natural gas, distillate fuel oil and propane are the main energy providers as well as a small amount of renewable energy that is mostly biomass.

Spatial variation in climate determines building shell design and the demand for energy services such as heating and air conditioning. The residential sector model accounts for this variation by dividing the total stock of single-family homes into two regions, a cold north region and a warm south region. The north region includes northern and interior states that have cold winters. The south region includes warm southern states and coastal areas. I used data from the Building Energy End-Use Model (BEEM) on projected number of households in each climate zone and projected demand for space heating, air conditioning, water heating and appliances.[19] Data for the commercial sector model are from the Commercial Buildings Energy Consumption Survey (CBECS) (EIA, 2005).

I did not have data on US building technologies and appliances so I used the technology data from the Canada model for both sector models, with adjustments to energy intensity and fuel mix. Further research is needed to tailor the building shell, space heating, ventilation and cooling technologies in this sector model to US data.

The residential and commercial sector models contain many technologies. For each building type – single-family homes, apartments, mobile homes, and the nine categories of institutional buildings, there is a separate set of heating technologies. Each set reflects the available choices of technology, performance level and fuel. In the residential model the range of heating technologies is simplified to the seven choices listed in Box 2. In the commercial sector model there are over 40 heating technology options for most building types.

[19] Data from David B. Belzer, Technology Planning & Deployment Group, US Department of Energy, Pacific Northwest National Laboratory, Richland, WA, March 2006.

Box 2. Residential heating technologies

- Electric heat pump
- Electric baseboard
- Integrated natural gas furnace and hot water boiler
- Natural gas furnace
- Natural gas furnace, high efficiency
- Oil furnace
- Wood stove

As well as heating technology choice, the models simulate the evolution of building shells. The demand for heating depends on the amount of insulation in the building shell and on the climate region. Shell technology options include wall, roof and window upgrades.

Because of the heating technology options, the sector is able to substitute between electricity, natural gas and oil use when prices change. To investigate this, I ran simulations with alternative energy prices and an emission price. An increase in the electricity price causes a switch to natural gas and oil use, and a small reduction in total energy use. An equivalent increase in the natural gas price causes a switch to oil and electricity use. Overall energy demand reduces more for a natural gas price increase than for an electricity price increase. A greenhouse gas emission price reduces demand for oil and natural gas and increases demand for electricity. To examine these effects in more detail, see Table 19 in Appendix B, which contains the full set of responses of the US sector models to changes in prices.

I also estimated the price elasticity of energy demand using the residential and commercial models. Table 4 shows the own-price elasticity of energy demand from the CIMS-US model as well as estimates from the EIA's NEMS model. The third column is the range of estimates from earlier studies (Wade, 2003). Nearly all of the model estimates are in the range of estimates from earlier studies. However, the estimates produced by the CIMS-US model are noticeably more varied than those produced by NEMS. One of the CIMS estimates falls outside the range of other studies.

Table 4. Own-price elasticity of energy demand in US residential and commercial sectors

	Short-run own-price elasticity			Long-run own-price elasticity		
	CIMS-US model estimate[1] (5 year)	NEMS model estimate[2] (3 year)	Summary of other estimates[3]	CIMS-US model estimate[1] (20 years)	NEMS model estimate[2] (20 years)	Summary of other estimates[3]
Residential						
Electricity	-0.26	-0.34	0.00 to -0.80	-0.55	-0.49	0.00 to -2.50
Natural gas	-0.20	-0.30	0.00 to -0.88	-0.61	-0.41	0.00 to -3.44
RPP[4]	-0.58	-0.34	0.00 to -0.70	-2.59	-0.60	0.00 to -3.50
Commercial						
Electricity	-0.10	-0.20	-0.17 to -1.18	-0.37	-0.45	0.00 to -4.74
Natural gas	-0.24	-0.29	0.00 to -0.38	-0.86	-0.40	0.00 to -2.27
RPP[4]	-0.43	-0.28	-0.30 to -0.61	-1.58	-0.39	-0.55 to -3.50

Table notes:

1. Estimates of the price elasticity of demand were produced using the CIMS-US residential and commercial sector models by running simulations with alternative energy prices in the business-as-usual scenario, starting in 2010, and comparing forecasted energy demand in 2015 (short run) and 2030 (long run) with business-as-usual levels. Elasticities were estimated by assuming that the relationship between price and demand is described by $E = \alpha Q^{\beta}$, where E is price, Q is demand, α is a constant, and β is the price elasticity of demand. Prices in the range 0.9 to 1.5 of business-as-usual price were considered and α and β were estimated using linear regression.

2. From a study of the responses of the 2003 version of the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS) Residential and Commercial Demand Models (Wade, 2003).

3. From a survey of studies carried out between 1977 and 1993 (Wade, 2003).

4. Refined Petroleum Products.

Industrial sector models

There are seven industry sector flow models in CIMS. These include chemical manufacturing, industrial minerals, steel making, metal smelting, and pulp and paper. Other types of manufacturing that are less energy intensive such as machinery, electronics, textiles, food and beverages are represented in a sector model called *other* *manufacturing*. The seventh industrial sector model represents mining activities except coal mining. Coal mining is an energy supply sector.

Each industrial flow model simulates the unique manufacturing processes and technologies employed. However, common end-use energy services that are used in most industries – boilers, pumps, compressors, fans, blowers, conveyors and electric motors – are modelled by a common set of technologies. The EIA carries out a survey of energy use in the US every four years called the Manufacturing Energy Consumption Survey (MECS). The data from this survey provided energy use by manufacturing sector disaggregated by end-use.

Table 5 shows the business-as-usual emissions forecast from the US industrial sector models. The estimates include indirect emissions by the domestic electricity sector from the production of electricity for industry. Forecasts of sector output growth are from various economic forecasts. From the figures it is clear that other manufacturing and chemical manufacturing are two significant industrial sectors in the US in terms of greenhouse gas emissions. The chemical sector is forecast to grow at a higher rate than other manufacturing and in 2030 it has the most emissions. Both sectors use natural gas for two-thirds of their energy requirements. Electricity provides most of the remainder. Natural gas is mainly used for process heat and steam generation. Electricity is mainly used for pumps, compressors, mechanical equipment and various electro-chemical processes. Coal use is high in the steelmaking sector and is 17 percent of total industrial energy use. Less than 10 percent of industrial energy use is refined petroleum products.

Because each industrial sector model is unique and contains specialised technologies, building, checking and updating the models is time-consuming. To save time I assumed that the basic characteristics of industrial processes do not vary much between the US and Canada. This is likely to be realistic for most industrial sectors, but not for all. For example, the production of wood pulp for paper manufacture uses different sources of energy in the US than in Canada. Fortunately this sector is not a large source of US emissions.

Table 5. Industrial sector emissions in the US in the business-as-usual scenario

Industry sector ranked by emissions in 2010	Forecasted average annual growth in output	Direct and indirect emissions (million metric tonnes CO_2e) 2010	2030
Other manufacturing	0.9%	393	438
Chemical manufacturing	2.3%	377	552
Industrial minerals	1.7%	158	223
Steel making	0.9%	150	192
Metal smelting	0.7%	149	123
Pulp & paper	0.4%	97	80
Mining (excluding coal)	0.6%	70	76

The US chemical sector required a complete overhaul because the model used for Canada lacked various manufacturing processes that are important in the US industry. Because of the broad range of chemical products produced in the US I adopted a less-detailed model based on energy intensity of economic output in seven chemical manufacturing sub-sectors. A diagram of the US chemical sector model is included in Appendix C. Electro-chemical processes were also added to the model.

The industrial minerals, steel making and metal smelting sector models are similar to the Canada models. Production levels for each discrete industrial product – cement, glass, aluminium, copper, and so on – were set to discrete US data. The model therefore reflects the forecasted growth trends of US industry.

The main opportunities to reduce greenhouse gas emissions in the industrial sectors are improved efficiency in industrial minerals manufacturing processes, increased cogeneration in chemical manufacturing, and fuel switching and higher efficiency in boilers used in other manufacturing. Increased efficiency in pumps and compressors in chemical manufacturing also avoids indirect emissions by reducing electricity demand.

Energy supply sector models

There are five energy supply sector models in CIMS: electricity generation, petroleum refining, natural gas production, crude oil production, and coal mining. They are included with other sector models when calculating total energy demand because they consume primary and secondary energy. However, the output of energy supply models is linked to total energy demand.

The natural gas production sector model and the crude oil production sector model describe the upstream oil and gas industry, which includes oil and gas exploration, production, and transportation. The sector models distinguish between land-based and offshore production, and between different types of production. Different types of sweet and sour gas production are modelled in the natural gas production model and the crude oil production model includes light, medium and heavy oil, bitumen and synthetic crude oil production. The US has a small amount of unconventional oil production from oil shale. However, unlike Canadian oil sands, it has not been commercialised at a significant scale. I assume oil shale production grows quickly and reaches 2.3 percent of total crude oil production by 2030. In the US, the main opportunities for emission reductions occur in the natural gas production sector model. The biggest emission reductions in a policy scenario are achieved by increased leak detection and repair, increased use of lean burn compressor engines, increased acid gas injection and improved boiler efficiency. In the oil production sector model, reduced venting in heavy oil production and increased efficiency in unconventional production are also important. I assume that venting and fugitive emissions are included in the scope of climate policy regulations.

The petroleum refining sector model simulates refining activities that convert crude oil into refined petroleum products such as fuel oil, jet fuel and gasoline. The efficiency of a refinery depends, among other things, on the types of processes required. Energy and emission intensive processes such as hydro-treating and hydro-cracking are used to produce a greater share of desirable products. The extent to which these processes are employed depends on the grade of crude oil supplied. I used historic trends in refinery process energy use to forecast future trends. In my forecast, use of energy intense refining processes increases over time.

I added a component to the US refining sector model to simulate ethanol production because this is a growing source of transportation fuel in the US. Energy use for ethanol production is 2.5 percent of energy use in the refining sector model and 65 percent of this is from coal. I used a forecast of ethanol production based on the US government's renewable fuels standard that aims for 7.5 billion gallons of ethanol production by 2012. I used a slower growth rate after that and in my model ethanol production is 4 percent of transportation fuel production by 2030. Ethanol production is a fixed proportion of domestic refined petroleum products (RPP) production and not linked to ethanol demand.

Gas-to-liquids and coal-to-liquids are processes that convert natural gas and coal into synthetic transportation fuel. If oil prices remain high, these proven technologies could be widely adopted. In the AEO reference case, coal-to-liquids fuels enter the market in 2011 and make up 13 percent of distillate fuel supply by 2030 (EIA, 2006). I did not include these processes in the model. The model could be improved by adding alternative types of fuel production such as these.

The biggest opportunities for emission abatement in the petroleum refining sector model are fuel switching in steam generation, increased cogeneration, and increased efficiency and fuel switching in ethanol production.

The coal mining sector is not a significant source of emissions. The sector consumes transportation fuels but the main source of greenhouse gas emissions is methane emissions from open cast mining activities and abatement opportunities are limited.

The overall energy characteristics of the US industrial sector models, when energy supply sectors are included, are slightly different to the residential, commercial and institutional models. Energy demand is most sensitive to RPP and natural gas prices. If the RPP price is higher, the sector substitutes RPP with coal and natural gas. If the natural gas price is higher the sector substitutes natural gas mostly with RPP, as well as some coal and electricity. The effect of an electricity price increase is not as great – the sector substitutes some electricity with natural gas. A greenhouse gas emission price reduces coal use significantly as well as reducing natural gas and RPP use and increasing electricity use. A greenhouse gas price reduces direct emissions and increases overall electricity use in the industrial sector.

Electricity generation sector model

The CIMS US electricity sector model is similar in structure to the Canadian electricity sector model (the energy flow model diagram is included in Appendix C). Demand for electricity generation is separated into three categories; baseload, shoulder and peak. This is necessary because instantaneous demand for electricity varies considerably according to daily and seasonal patterns of consumption. As a result, a proportion of generating capacity must be operated intermittently according to instantaneous demand. Peak load plants only operate when demand is very high and are on stand-by most of the time. Base load generating plants operate year round with only short periods of downtime for maintenance. Shoulder load plants occupy the middle ground and include plants that operate on a seasonal basis. Not all types of generating plant can operate intermittently and the utilisation rate of a plant affects the generating cost. Therefore different technologies are needed to represent the types of generating plant that are available in each category with costs that reflect actual utilisation rates.

The proportion of electricity generation in each category was estimated from the load curves of different regions of the US. I found the proportions to be similar to those in the Canada model. Base load provides 74 percent of generation, shoulder load 20 percent and peak load 6 percent.[20]

The existing stock of electricity generating technologies was derived from a database of US power plants that included capacity factors (EIA, 2004).[21] I assumed that nuclear plants and renewable energy generation, with the exception of large hydroelectric facilities, are only available for base load generation. Coal, natural gas and oil-fired plants with high capacity factors provide the remainder of baseload. I assumed that the remaining coal plants provide shoulder load and I assigned natural gas-fired generating plants with capacity factors less than 35 percent to peak load generation. I assumed most

[20] An adjustment to the peakload and baseload categories is necessary to account for pumped storage, which is a way of providing peak demand using off-peak (baseload) generation.

[21] A capacity factor is a measure of plant utilization and is the percentage of time that a plant is operating in a typical year.

hydroelectric generation in the US provides peak load generation but I allowed for future baseload hydroelectric power from small run-of-the-river installations.[22]

Renewable energy technologies in the base load category include geothermal, municipal solid waste combustion, landfill gas combustion, integrated gasification combined-cycle (IGCC) biomass, solar thermal, solar photovoltaic, and wind turbines. To simulate constraints on renewable resources I limited the allowable growth of municipal solid waste, landfill gas combustion, biomass, wind and geothermal generation. A more thorough analysis of renewable energy potential in the US would improve the model. Ideally, cost curves should be used instead of fixed limits on capacity growth. In the real world the cost of most renewable energy resources increases with total capacity installed because resource quality is heterogeneous and lowest cost capacity is usually installed first.

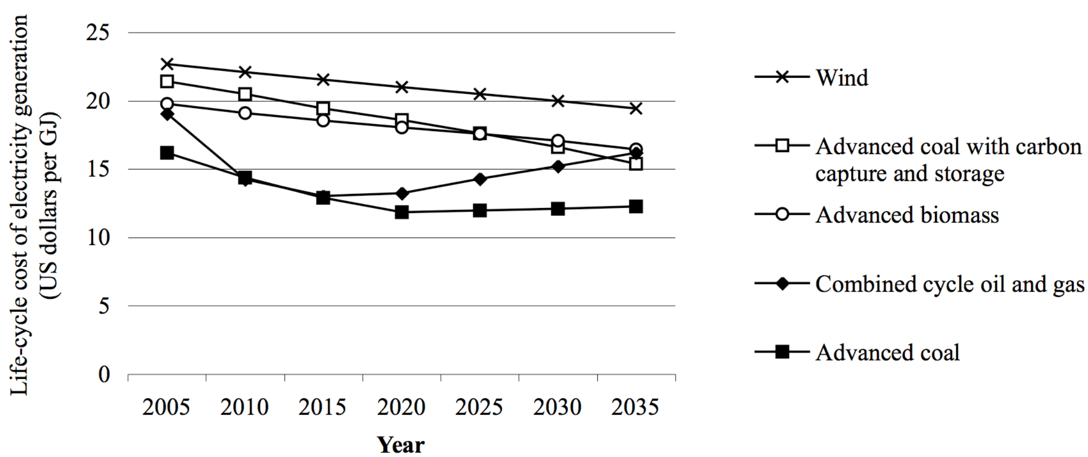
Equally important in modelling renewable energy are the effects of learning-by-doing and economies-of-scale. CIMS has a declining capital cost function to simulate how learning-by-doing reduces the cost of technologies. I applied this to renewable and other alternative electricity generation technologies. Figure 7 shows how the lifecycle cost of these base load generation technologies evolves in the BAU scenario. The costs decline over the simulation period, with the exception of combined cycle oil and gas, which increases as the cost of oil and gas increases in future years. The cost and efficiency of generating technologies in the US model is based on data used in the NEMS electricity market module (EIA, 2006). Transmission losses are static. I did not look at trends in transmission losses and technologies that increase transmission efficiency.

The future use of nuclear-powered generation is difficult to simulate because the decision-making process is influenced by many factors other than cost. Even cost is uncertain because the cost of future disposal or storage of spent nuclear fuel is not known. Opposition from local communities inhibits construction of nuclear plants. New capacity tends to be sited at existing facilities. Rather than attempt to simulate these factors explicitly, I decided to adjust the cost of new nuclear generation so that the

[22] Run-of-the-river is a term used to describe hydro-electric facilities installed on small rivers and creeks where there is usually limited capability to store water behind a dam.

amount of total generation from nuclear power does not increase in the business-as-usual scenario. This was achieved by adding an intangible cost that is 25 percent of its capital cost. This method allows nuclear capacity to be higher in policy scenarios when alternatives are costly.

Figure 7. Forecasted lifecycle cost of electricity generation in the US



Although the electricity sector model structure is similar for the US and Canada, the primary energy mix in the US and Canada is quite different. The first bar in Figures 8 and 9 shows electricity generation in 2005 by primary energy source. The US electricity sector is predominantly fossil-fuel-based with a considerable amount of generation by nuclear plants. Canada's electricity generation is predominantly hydroelectric; fossil fuels and nuclear are less significant.

Figure 8. Electricity generation technology in the US

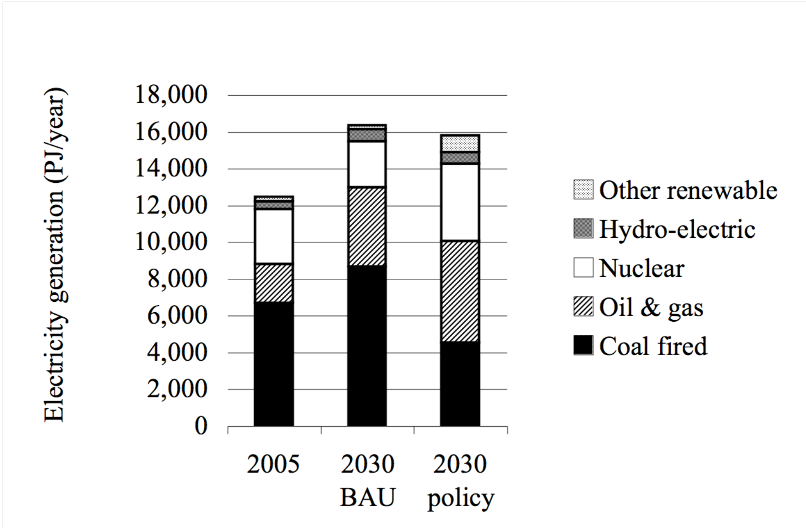
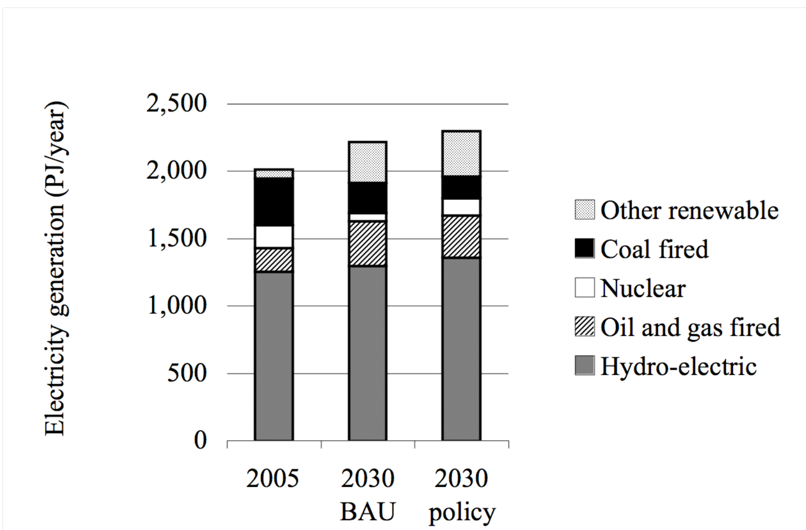


Figure 9. Electricity generation technology in Canada



Because of the significant differences in the composition of the initial capital stock in the two countries the emission intensity of electricity generation is different. The initial capital stock also determines what potential there is in each country for future emission reductions.

Most of the emission reductions in both electricity sector models are a result of changes in baseload generation technologies. Significant reductions in emissions occur in the US model when existing coal plants are replaced by gas-fired and nuclear power plants and when new coal plants include integrated gasification combined cycle (IGCC) and IGCC with carbon sequestration. I also allowed existing coal plants to be retired prematurely and replaced with new IGCC plants. When climate change policies are simulated, the fate of fossil-fuel-fired generation depends on the cost of low-emission technologies. In some policy scenarios fossil-fuel-fired generation does not decline.

Over three quarters of the difference between fossil-fuel-fired generation in the business-as-usual (BAU) and in the policy simulation is explained by increased nuclear generation. There is almost twice as much nuclear generation with a policy than in the BAU. The rest is accounted for by increased renewable generation including hydro. Biomass combustion, geothermal and wind generation increase to levels up to 10 times higher than in the BAU scenario. I did not simulate the possibility of carbon capture and storage in biomass fired IGCC generation. Hydro generation increases 25 percent. Despite the large relative increase in the amount of renewable generation, it accounts for less than 10 percent of total generation in 2030 when a policy is simulated.

Changes in shoulder load generation also lower emissions in a policy simulation but peak load technologies have a very small impact. I found that the possibility of increased energy storage capacity would not have a significant direct effect on emissions because the emission intensity of baseload and peakload generation is similar in the US. However, energy storage is an enabling technology that could increase the potential for renewable generation. There is some switching between oil and gas fired generation in dual-fuelled plants but its impact is also small.

The biggest effects on energy use and emissions in the electricity generation sector model occur when an emission price is simulated. Coal use reduces initially, natural gas use is higher, and total emissions are reduced by over 500 million metric tonnes in 2030. However, the prices of natural gas and coal also have an impact on energy use and emissions. With a higher natural gas price there is less natural gas use in electricity generation and emissions increase because coal use increases. A higher coal price has the opposite effect. The price of refined petroleum products plays a minor role.

Transportation sector model

The energy flow model of the US transportation sector is similar to the Canadian model and includes personal and freight transportation. Freight transportation includes rail, air and marine modes. Personal transportation is divided into urban and long distance. Long distance personal transportation includes rail, air, bus and car use. Within urban personal transportation, there is mode switching between personal vehicles, mass transit, cycling and walking. Personal vehicles may have single- or high-occupancy, allowing for the possibility of increased car sharing. To simulate the real disadvantages of transit, walking and cycling, these modes of transportation are assigned high intangible costs in the model that prevent them from gaining unrealistic market share.

I used demand forecasts from the Annual Energy Outlook 2006 for total personal and freight transportation (EIA, 2006). For more disaggregate information on travel demand I used data from surveys of the population that determine personal travel demand, preferences and vehicle usage (Hu and Reuscher, 2004). I also updated most of the transportation technologies to reflect US vehicle stocks. Data from the EIA on transportation fuel use and vehicle efficiency were used to determine vehicle efficiency and to calibrate the model (EIA, 2005). Comprehensive data on freight transportation were not available.

Comparing US data with the Canada model suggests that people in the US travel more than Canadians and that there is 60 percent more freight transportation per capita in the US than in Canada. US freight transportation is forecast to grow on average 2 percent a year compared to 1.2 percent in Canada. Personal transportation demand grows at 1.8 percent a year in both countries. I can speculate why freight transportation in the US may be growing faster but I do not know whether the forecasts reflect real differences between the two countries. The difference could be due to forecast uncertainty, especially since the forecasts for each country were produced at different times and by different organisations. The data also indicate that people in the US use public transit half as much as in Canada. Other important characteristics of transportation demand such as average vehicle occupancy and urban-rural shares of total transportation are similar in both countries.

The transportation model used for this research lacks important features that could significantly alter forecasts of energy use and emissions. There are no opportunities for improved technology in air, rail or marine transportation and the possibility of mode shifting in long distance personal transportation and freight transportation is not included. Improvements to these areas should be incorporated into the model.

The model includes a variety of cars and light trucks used for personal transportation. Figure 10 shows market share forecasts for selected technologies in the model. In 2005 the vehicle stock is mostly conventional gasoline vehicles, with a small fraction of hybrid gasoline-electric, diesel and ethanol-fuelled vehicles. Hybrids and plug-in hybrids are popular vehicles based on lifecycle cost. By 2030, they provide about a third of vehicle demand in the business-as-usual scenario.

Figure 10. Forecasts of personal vehicle use in the US

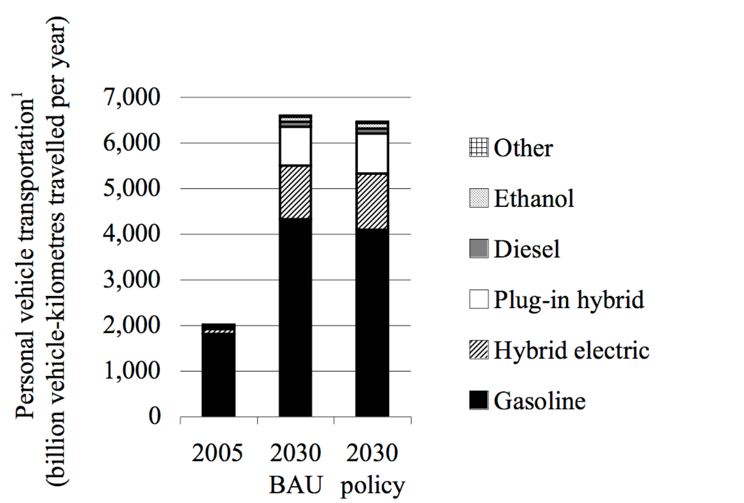


Figure notes:
1. Cars and light-duty trucks used for urban and long-distance transportation.

Other technologies in the model, such as battery-electric vehicles, hydrogen fuel cell vehicles and vehicles that use alternative fuels other than ethanol and diesel do not gain a noticeable share of the market. In simulations with a climate policy the proportion of hybrids and other alternatives is higher but only by a few percent. Total personal vehicle use declines with a policy because of mode switching and higher vehicle occupancy.

Emission intensity improvement

Because of the number and complexity of sector flow models, it is difficult to comprehend the overall behaviour of energy demand and greenhouse gas emissions when prices change. In this section and the next, I summarise the combined behaviour of the models by looking at two sets of characteristics of energy-economy models, the rate of change of emission intensity, and elasticities of energy demand and greenhouse gas emissions. These characteristics help explain the final results in Chapter 5 when the integrated model is used to simulate the combined energy system of the US and Canada.

Emission intensity is introduced earlier in this chapter and the change in emission intensity in the business-as-usual simulation is described. The aim of a climate policy is to reduce emission intensity faster than it would decline in the business-as-usual.

When I simulated an emission price policy in all sectors, emission intensity declined faster or grew slower, as expected. The average annual rate of improvement in emission intensity in the residential, commercial and institutional sector increased from 0.7 to 2.4 percent in the US and from 1.0 to 1.6 percent in Canada. The rate of improvement in transportation emission intensity increased by 0.3 percent in both countries. In the US, the rate of improvement in the emission intensity of industry increased from 0.4 percent to 1.1 percent with a policy. In Canada, the business-as-usual growth in emission intensity of industry reduced from 0.8 to 0.1 percent with a policy. In the US electricity generation sector, the rate of improvement in emission intensity increased from 0.4 percent to 2.6 percent. This dramatic improvement rate is achieved by the rapid adoption of improved coal technologies and carbon capture and storage. Table 20 in Appendix B summarises the emission intensity growth rates with and without the climate policy.

Elasticity of energy demand and emissions

The fifteen sector models together provide a model of total energy demand and emissions in each country. The combined model provides a forecast of energy demand and emissions given future sector output, energy prices and policy such as a price on emissions. The dynamics of each country's total energy demand can be characterized by estimating the elasticity of demand and the elasticity of greenhouse gas emissions. The price elasticity of demand is the percentage change in demand caused by a change in price, divided by the percentage change in the price. The estimates from the CIMS sector models are shown in Table 6 for long-run changes in demand occurring twenty years after a price change is introduced. In order to measure the isolated effects of individual prices, I held sector output constant and modified one price at a time.

Own-price elasticities occupy the cells on the diagonal from top left to bottom right of each set of elasticities. Own-price elasticity of demand is negative because demand for a commodity reduces if its price is increased. In the case of energy demand, consumers switch to alternative fuels, reduce energy use by improving efficiency, or reduce their consumption of energy services. Natural gas demand is the most sensitive to its own price, especially in the US model. Demand for refined petroleum products is more elastic in the Canada model than in the US. Coal demand and natural gas demand are more elastic in the US model. The figures in the rest of the table are estimates of cross-price elasticity. That is, the sensitivity of demand for one commodity to changes in the price of another. Cross-price elasticities indicate the amount of substitution that occurs between one commodity and another.

The highest cross-price elasticity is the elasticity of coal demand with respect to natural gas price. It is especially high in the US model. A ten percent increase in the price of natural gas in the US causes a 7.7 percent increase in coal demand. The natural gas price also has a big effect on the demand for other energy commodities. A ten percent increase in the price of natural gas in Canada causes a 2.9 percent increase in electricity demand and a 2.4 percent increase in RPP demand.

Table 6. Estimates of long run elasticity of energy demand and greenhouse gas emissions

(a) US

	Elasticity of electricity demand	Elasticity of refined petroleum products demand	Elasticity of coal demand	Elasticity of natural gas demand	Elasticity of greenhouse gas emissions
with respect to:					
Electricity price	-0.37	0.02	0.00	0.14	0.04
Refined petroleum products price	0.07	-0.30	0.08	0.06	-0.09
Coal price	0.00	0.02	-0.89	0.33	-0.15
Natural gas price	0.13	0.12	0.77	-0.94	0.12
Greenhouse gas price[3]	0.08	-0.06	-0.48	-0.06	-0.19

(b) Canada

	Elasticity of electricity demand	Elasticity of refined petroleum products demand	Elasticity of coal demand	Elasticity of natural gas demand	Elasticity of greenhouse gas emissions
with respect to:					
Electricity price	-0.39	0.01	0.00	0.11	0.04
Refined petroleum products price	0.01	-0.45	0.01	0.10	-0.08
Coal price	0.00	0.00	-0.34	0.06	-0.03
Natural gas price	0.29	0.24	0.42	-0.71	-0.02
Greenhouse gas price[3]	0.30	-0.06	-0.45	-0.21	-0.17

Table notes:

1. Estimates of the long run price elasticity of demand were produced by running simulations with alternative energy prices in the business-as-usual scenario, starting in 2010, and comparing forecasted energy demand in 2030 with business-as-usual levels, with sector output, trade and all other prices fixed. Elasticities were estimated by assuming that the relationship between price and demand is described by $E = \alpha Q^{\beta}$, where E is price, Q is demand, α is a constant, and β is the price elasticity of demand. Prices in the range 0.9 to 1.5 of business-as-usual price were considered and α and β were estimated using linear regression.
2. Energy price elasticity estimates are based on energy price adjustments in the range 0.9 to 1.5 times forecasted prices.
3. Greenhouse gas emission price elasticity estimates are based on emission prices in the range 10 to 100 dollars.

Table 6 also shows elasticities of greenhouse gas emissions and the effects of changes in the greenhouse gas emission price. In the US model, greenhouse gas emissions decrease when the prices of refined petroleum products or coal are higher, and increase when the price of electricity or natural gas is higher. This is because electricity and natural gas are zero- or low-emission at the point of use and so switching to them reduces sector emissions. Switching away from them to high emission fuels increases emissions. Sector output is fixed in these experiments, so the elasticity estimates ignore the adjustments that would occur on the supply side to keep supply and demand in balance.

I also estimated the short-run elasticity of demand over a five-year time period. The short run estimates are roughly one third of the long-run estimates. This is because in the short run less equipment and technology reaches the end of its life, so there is less opportunity to replace capital stock with new and alternative technology.

Table 7 summarizes in a qualitative way the important behaviours of the sector models in response to prices. In each price scenario, I describe the large changes in energy demand or emissions that explain most of the overall demand response. Using this table it is possible to identify the role that each sector plays in determining the elasticity of demand and emissions.

Table 7. Summary of effects of price increases on sector models

Scenario	Effect
Higher electricity price	▪ Residential, commercial and institutional sector substitutes electricity use with natural gas and RPP ▪ Emissions increase, mainly in residential, commercial and institutional
Higher RPP or crude oil price	▪ Transport sector reduces RPP use ▪ Residential, commercial and institutional and industry sectors substitute RPP use with natural gas and electricity ▪ Industry sector substitutes some RPP with coal ▪ Emissions reduce, mainly in transportation
Higher natural gas price	▪ Electricity sector substitutes natural gas with coal ▪ Residential, commercial and institutional sector reduces natural gas use and substitutes some of it with RPP and electricity ▪ Industry sector reduces natural gas use and substitutes some of it with RPP ▪ Energy use and emissions in electricity generation increase
Higher coal price	▪ Electricity sector reduces coal use and substitutes some of it with natural gas ▪ Emissions in electricity generation reduce
Higher greenhouse gas emission price	▪ Electricity sector reduces coal use and substitutes some of it with natural gas ▪ Transportation sector reduces RPP use ▪ Residential, commercial and institutional sector reduces RPP and natural gas use and substitutes some of it with electricity ▪ Industry sector reduces coal, natural gas and RPP use and substitutes some of it with electricity ▪ Emissions reduce in all sectors

Table notes:
RPP = refined petroleum products

Emissions avoided

Finally, Table 8 shows the sectors in which the greatest emission reductions occur when a climate policy is simulated. These results are from a simulation of the combined US-Canada model with energy supply-demand equilibrium and trade. The integrated model is explained in the next chapter, but it is useful to review these results here because they reflect the characteristics of the sector models of each country. Because energy supply and demand is balanced in these simulations, the changes in energy demand by sectors such as commercial and residential is taken into account and the production of energy by electricity generation and other supply sectors is adjusted accordingly.

In the US, over 1 billion metric tonnes of greenhouse gas emissions are avoided in the electricity generation sector due to the policy. This is 87 percent of all emissions reduced. This result emphasizes the very large potential for emission reductions in this sector compared to all other US sectors. The transportation sector is a significant source of emission abatement and could be more so if the aforementioned model improvements were implemented.

In Canada, avoided emissions are spread across more sectors. The top five sectors together account for 87 percent of emissions avoided in 2030. In Canada the crude oil production sector is the most significant source of emission abatement and electricity generation is responsible for only 16 percent of emissions avoided. The pulp and paper and natural gas production sectors are also a significant source of emission abatement.

Table 8. Sectors that experience the most greenhouse gas emission abatement with a policy – US and Canada

(a) US

Sector	**Business-as-usual emission forecast (million metric tonnes CO_2e)** 2010	2030	**Greenhouse gas emissions avoided in 2030 with a policy[1] (million metric tonnes CO_2e)**	
Electricity generation	2,227	2,659	1,020	(87%)
Transportation	2,247	3,043	104	(9%)
Natural gas production	264	311	25	(2%)
Petroleum refining	218	302	10	(1%)
Commercial	182	252	6	(1%)
Other sectors	1,200	1,379	13	(1%)
Total	6,338	7,947	1,179	(100%)

(b) Canada

Sector	**Business-as-usual emission forecast (million metric tonnes CO_2e)** 2010	2030	**Greenhouse gas emissions avoided in 2030 with a policy[1] (million metric tonnes CO_2e)**	
Crude oil production	67	211	47	(50%)
Electricity generation	100	81	15	(16%)
Transportation	180	214	11	(12%)
Pulp & paper	11	14	6	(6%)
Natural gas production	70	53	4	(4%)
Other sectors	186	220	12	(13%)
Total	615	794	94	(100%)

Table notes:

1. Results of a simulation of a slow-shallow carbon price path with trade effects. Only direct emissions are included in these estimates. Percentages show proportion of total emissions avoided.

CHAPTER 4: INTEGRATED MODEL

This section describes how I constructed an integrated US-Canada model by simulating energy trade between Canada, the US and the rest of the world (ROW). The objective of simulating energy trade between countries is to take account of changes in supply and demand (including prices) when energy-environment policies are adopted. When energy supply and demand are in equilibrium, total energy supply equals demand. Market price is the arbitrator in this relationship. The quantity supplied at a given price must equal the quantity demanded at that price.

The three effects that could alter this equilibrium are (1) changes in energy demand as a result of an emission price or a change in the price of energy (including substitutes), (2) changes in the cost of energy production due to changes in energy or emission prices in supply sectors, or changes in the quantity produced and (3) changes in energy use in energy production sectors as a result of changes in the quantity produced. For simplicity, I am only interested in modelling commodities for which the supply and demand equilibrium is likely to be significantly affected by policies.

The production cost of any good that requires energy to produce will be affected by changes in energy prices and policies that put a price on emissions. Table 9 shows the emission intensity of production of the five major energy commodities in CIMS. From these results I concluded that the cost of coal production is not affected significantly by emission charges. Although the demand for coal in the US is quite likely to change significantly when there is a price on emissions, changes in the emissions from coal production will not have a big impact on total emissions because of the low emission intensity. Could a change in demand cause the cost of production to adjust? I decided that long-run changes in the cost of coal production are unlikely to be significant because it is an abundant resource.[23] Based on this argument, I omitted coal supply from the model.

[23] According to the US Energy Information Administration the ratio of global reserves to production is approximately 160 years.

Combustion of coal by the demand sectors is accounted for in the sector models so changes in the direct emissions from the use of coal are taken into account.

Table 9. Emission intensity of energy production

Energy commodity	**Emissions per unit output (metric tonnes of CO_2e per gigajoule)**
Electricity	0.159
Natural gas	0.015
Crude oil	0.009
Refined petroleum products	0.005
Coal	0.001

Data source: CIMS model

I then looked at international trade in energy. By far the biggest energy trade flow in 2005 was the import of crude oil by the US from the rest of the world. The next biggest trade in terms of embodied energy was US imports of refined petroleum products (RPP). Figure 11 is a schematic diagram that illustrates the relative size of the major energy imports in North America in 2005 (those greater than a thousand petajoules a year). As well as US imports from the rest of the world (ROW), imports of natural gas, crude oil and RPP from Canada are significant, as are Canadian imports of crude oil from ROW. Coal is exported to ROW by both the US and Canada but the quantity in 2005 is not enough to be included in the diagram.

I also looked at the reference case forecast of energy trade in 2030. The biggest single change is a quadrupling of Canadian crude oil exports to the US, from 2,900 petajoules in 2005 to 11,700 petajoules in 2030. US imports of natural gas and RPP from the rest of the world also increase significantly. Therefore including these energy flows in the trade model is important. RPP and electricity trade across borders is much less significant in terms of the quantities involved. However, I included them so that the trade model is identical for each commodity.

Figure 11. Schematic diagram of major energy imports in 2005.

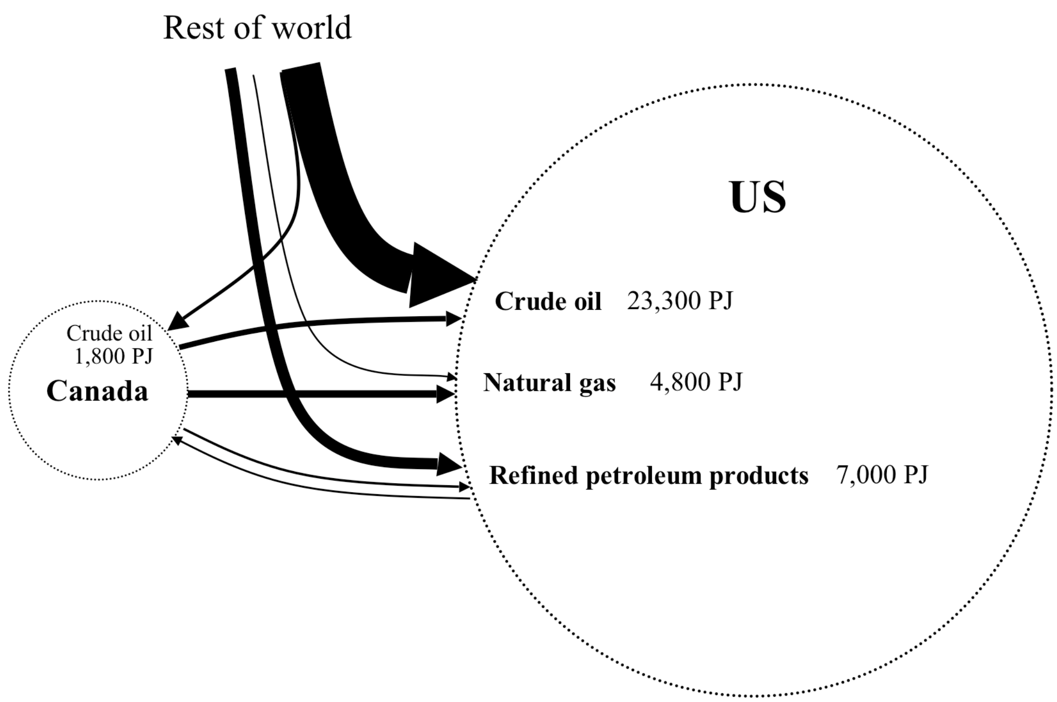


Figure Notes:
1. PJ = Petajoules
2. Energy flows less than 1,000 PJ per year not shown.
3. Thickness of lines proportional to quantity of energy
4. Area of circle proportional to total energy demand by country

The only significant energy shipment out of North America is exports of refined petroleum products by the US. These exports are mostly petroleum coke and fuel oil, the by-products of gasoline production. It is the only significant export to ROW and I decided to exclude it from the model so that I could ignore rest-of-world demand entirely. The resulting integrated model contains six components: two energy demand models, a model of trade, and three energy supply models. The two demand models are the two sets of sector flow models of the US and Canada described in the previous chapter. The three models of energy supply by the US, Canada and ROW are described later in this chapter.

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Trade model

Armington (1969) proposed that products of different countries may be treated as imperfect substitutes. In other words, consumers in one country consider domestic production and imports from another country to be similar but not identical products in a weakly separable product category where differentiation is by country of origin. Assuming well-behaved preferences, the Armington model can be used to describe how demand is met by a combination of domestic production and imports from other countries using a constant elasticity of substitution (CES) function (Francois and Hall, 1997). A CES function is a mathematical function that is commonly used in economic models to relate inputs to outputs when representing production. It assumes elasticities are constant even as relative factor shares change.

I define an Armington composite of energy goods Q_c, for each country c that consumes goods. Q_c is a composite of the energy goods produced in all countries X_s, $s=1...n$, including domestic production ($s=c$)

$$Q_c = \left[\sum_{s=1}^{n} \omega_{c,s} X_s^{\rho} \right]^{\frac{1}{\rho}}$$ **Equation 3**

where $\rho = \frac{\sigma - 1}{\sigma}$ and σ is the elasticity of substitution. ω is a constant that is set during calibration. I calibrate the model to a reference case so that prices are unity in the business-as-usual (BAU) scenario. The price of the composite of energy goods P_{Ac} in each market is a function of the supply price P_s in each supply country

$$P_{Ac} = \left[\sum_{s=1}^{n} \omega_{c,s}^{\sigma} P_s^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$$ **Equation 4**

The quantity of goods produced in country s and supplied to country c, $X_{c,s}$ is a function of the supply price of the good, the composite price in country c and total expenditure $Y_c = P_{Ac} Q_c$ in country c

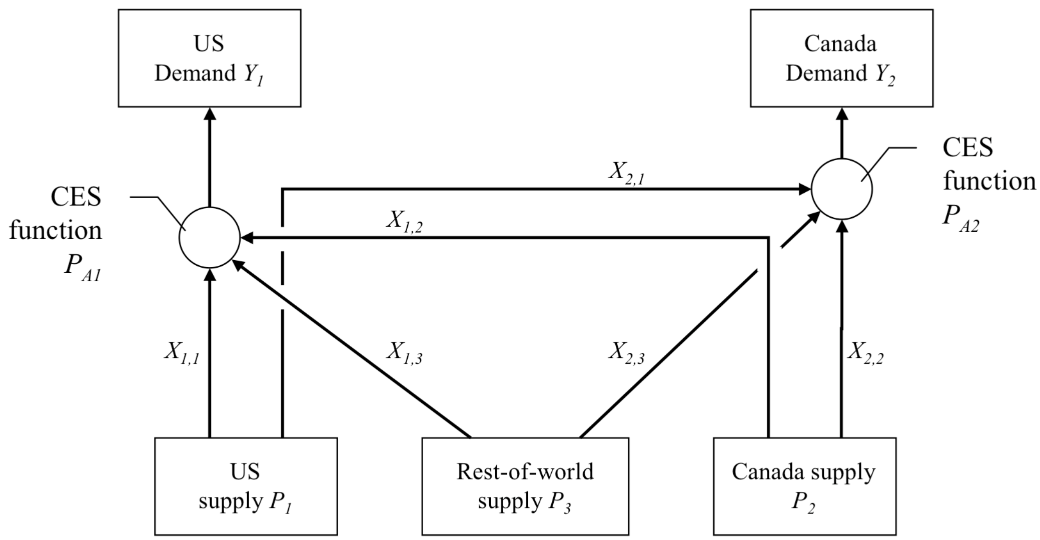
$$X_{c,s} = \left[\frac{\omega_s}{P_s} \right]^{\sigma} P_{Ac}{}^{\sigma-1} Y_c \qquad \textbf{Equation 5}$$

I use these equations in combination with the energy supply and demand models of each country to simulate trade between the US and Canada and supply by the rest of the world (ROW). Each supply and demand model contains three supply models (US, Canada, and ROW) and two demand models (US and Canada), as shown in the diagram in Figure 12. There is a similar trade model for each of the four energy commodities.

Total energy demand in each country is the sum of energy demand in each sector, including energy supply sectors, calculated by the 15 sector models in the CIMS model. Crude oil demand is exceptional. It is a function of domestic RPP production.[24] Energy demand calculated by the sector models is a complex function of energy prices, technology stock and sector output. CIMS calculates an average financial lifecycle cost (FLCC) for each sector. The FLCC in the supply sectors is used to calculate the supply price and is also a function of energy prices, technology stock and sector output. In the case of ROW there is no CIMS model so a separate supply model is used.

[24] In the CIMS model, crude oil demand is a function of the output of the petroleum refining sector. An exogenous constant known as refinery gain defines the amount of crude oil required to produce a unit of refined petroleum products.

Figure 12. Diagram of the US-Canada energy trade model



This system of supply and demand models connected by CES functions is described by a set of 13 simultaneous equations. There are 13 unknown variables in each trade system, 3 supply prices, 2 composite energy prices, 2 expenditures and 6 supply quantities. These variables are described in Table 10.

The four models of trade in each commodity are not independent because unknown variables such as composite energy prices appear in all four sets of equations. Therefore, the complete model of supply and demand of the four energy commodities is a set of 52 equations (4×13) with 52 unknowns. To solve this multidimensional non-linear system in each time period I use a numerical solver that employs the Newton-Raphson method of root finding (Press et al, 2002). The algorithm starts with initial values for the unknowns and calculates a matrix of partial derivatives that is used to find a solution in a series of iterations. The model is solved in each time period consecutively. The solution in one time period determines the solution in the next, through cumulative production levels and the technology stocks in the sector models.

Table 10. Energy trade model variables

Supply prices (price index)	
P_1	US production
P_2	Canadian production
P_3	ROW production
Composite energy prices (price index)	
P_{A1}	US market
P_{A2}	Canadian market
Expenditure (total demand × price index)	
Y_1	Total expenditure by US
Y_2	Total expenditure by Canada
Supply quantities (physical units)	
$X_{1,1}$	US production for domestic market
$X_{1,2}$	US imports from Canada
$X_{1,3}$	US imports from ROW
$X_{2,1}$	Canadian imports from US
$X_{2,2}$	Canadian production for domestic market
$X_{2,3}$	Canadian imports from ROW

Because of the complexity of the CIMS models, I did not attempt to derive algebraic expressions for all partial derivatives. Instead, I used finite difference experiments to estimate them.[25] The drawback of this approach is that the CIMS models must be calculated numerous times before a solution is found. Because of implementation issues, the CIMS software used for this project wastes considerable computational effort reloading data and repeating unnecessary calculations. Consequently, each iteration of the numerical solver takes around 30 minutes to complete. Usually 4 to 7 iterations are required to find a solution in one time period, so a complete simulation involving equilibrium in 5 time periods typically takes 8 to 11 hours. Improvements to the program code would reduce the time significantly. The solver is reasonably reliable. Only during sensitivity analyses when extreme parameter values were investigated did convergence

[25] In a finite difference experiment an independent variable is adjusted by a small amount and the dependent variables are re-calculated. The ratio of the change in a dependent variable to the change in the independent variable is an estimate of its partial derivative with respect to the dependent variable.

problems occur. The computational performance and reliability could be further improved by adopting more sophisticated root-finding algorithms such as Broyden's method (Press et al, 2002).

To complete the trade model I needed estimates of the Armington elasticity of substitution for the four energy commodities in the energy trade model. Armington elasticities are estimated by analysing historic trade data. I could not find many studies that provide estimates of Armington elasticities for energy commodities. A study by Reinert and Roland-Holst (1992) provided estimates for US mining and manufacturing sectors in the range 0.14 to 3.49. The estimate for crude petroleum and natural gas was 0.31. A study by Gallaway, McDaniel and Rivera (2002) produced disaggregated estimates for manufacturing that included an estimate for the short run elasticity in petroleum refining of 0.85.

A review of the research by McDaniel and Balistreri (2002) found that estimates vary considerably. Long-run estimates are higher than short-run estimates; more disaggregated analyses find higher elasticity; and the results are sensitive to the estimation technique used. They also report that "many trade economists view these elasticity estimates with scepticism and believe that domestic and imported goods are much more substitutable than most estimates suggest" (pp. 22, McDaniel and Balistreri, 2002).

One comprehensive source of substitution elasticities for energy trade that I found was the Global Trade Analysis Project (GTAP). I decided to choose values similar to the values used in their model. They are a lot higher than the estimates from the older studies mentioned above. Table 11 shows the default values of σ that I used for each of the four energy commodities in my model, as well as the values used in the GTAP model (Dimaranan et al., 2006). The GTAP model has two separate substitution functions that use different values of σ. One is for the substitution of domestic production with imports and one is for the substitution between imports from different countries. My model uses only one substitution function for all sources of supply. I decided to use the lower GTAP elasticities that reflect the substitutability of domestic production with imports. This seemed to me to be the most important behaviour to simulate well. Consequently, the substitutability of imports from different countries could be underestimated in my model. This would mean that more US imports from Canada might be replaced with imports from the rest of the world in a policy scenario where Canadian supply price was higher.

I used an Armington estimate of 3.6 for natural gas supply (Hummels, 1999). It is much lower than the GTAP figure. I am not sure why the GTAP figures for natural gas are as high as 17 and 34. Whatever the reason, using such high values in the US-Canada model caused huge adjustments in natural gas supply that were not realistic. It may be appropriate to use lower values of Armington elasticities for short run trade adjustments in the early model time periods. This research would benefit from an informed analysis of substitution elasticities for energy supply in North America.

Table 11. Armington elasticity of substitution – energy trade.

Commodity	Armington elasticity of substitution (σ)	GTAP values[1] Domestic production vs. imports	GTAP values[1] Sourcing of imports
Electricity	2.8	2.8	5.6
Refined petroleum products	2.1	2.1	4.2
Natural gas	3.6	17.2	34.4
Crude oil	5.2	5.2	10.4

Table notes:
1. Substitution elasticities used in the Global Trade Analysis Project (Dimaranan et al., 2006).

Supply price models

In order to determine the energy supply price P_s in the energy trade model, I developed supply price models for each energy supply sector in each country. For the US and Canada, the CIMS sector models determine how the cost of energy production is affected by changes in energy prices, technologies and emission price and the supply model adjusts supply price according to cumulative production. For ROW, there is no

CIMS model and so the supply model determines supply price based on quantity of energy supplied or cumulative supply.

As previously mentioned, CIMS calculates an average financial lifecycle cost (FLCC) for each sector. Most energy supply markets are competitive and so the market price is determined by the marginal cost of production. The exceptions are some electricity markets where a regulated monopoly supplies electricity and the price is usually equal to the average cost of production. For scarce non-renewable resources such as petroleum crude and natural gas, the marginal cost of production may greatly exceed the average cost of production because new capacity generally requires high cost non-conventional production technologies. In these cases, the FLCC parameter cannot be used to represent the supply price in the market.

In the crude oil and natural gas sector models, non-renewable resource scarcity and the shift to more costly extraction and processing technologies is represented by a fixed time trend. The proportion of total output that each technology supplies is specified in each time period. This means that the FLCC parameter reflects changes in the average cost of production over time as a result of diminishing resource quality. However, because the trend is fixed it cannot account for alternative demand scenarios, such as higher production growth where production costs rise faster because the resource is exploited faster.

This limitation of the FLCC parameter can be demonstrated by investigating its characteristics in a single time period. I varied output in the supply sectors in one time period, while holding energy prices constant. I found that the FLCC estimates of the average cost of production produced a declining supply cost curve. This is because new technologies gaining market share in the model tend to be lower cost than existing technologies that are in decline. In reality, this technological progress is accompanied by the effect of increasing marginal costs because the increase in output must be met with marginal technologies.

Finally, CIMS supply sector models do not generally include all technologies and all costs associated with production so the FLCC parameter may underestimate the total cost of production.

Because of the limitations of the FLCC parameter, I developed a new and more versatile model of supply price. This model is useful for simulating the supply of crude oil and natural gas. Their rising costs of production play a role in supply and demand. I still use the FLCC parameter to determine the effect of changes in energy prices and emission charges on the cost of production, but the long-run trend of production cost is simulated by the supply price model and is determined by cumulative production.

When modelling the production of a non-renewable resource such as crude oil or natural gas, it is necessary to take into account two important phenomena. As a resource is developed the production costs per unit of production may increase because the remaining resource is lower quality or requires more effort to find and extract. On the other hand, over time and with increasing production, technological progress and economies-of-scale work to reduce the cost of finding and producing and thus extend the amount of resource that is economically extractable.

The total recoverable oil and gas resource is unknown. However, its discovery, development and production behave more like a traditional manufacturing flow process than true non-renewable resource extraction. The inventories of undeveloped and developed reserves are replenished in response to market prices (Adelman, 1992). Nevertheless, eventually there comes a point where the cost of finding, developing and producing new resources increases and the market price will increase until a substitute is found or until demand tails off. I assume that current high oil prices are mostly a result of short run supply and demand issues, but that a steady increase in the long run average cost of production is occurring despite technological progress. What this increase is likely to be is hard to know but I assumed it is steeper in Canada and the US than in the ROW where oil production is still low cost and reserves are thought to be relatively abundant.

To incorporate the combined effects of resource depletion and technological progress I use a model where the long run average cost of production in the reference scenario, P_{LRAC}, is a linear function of cumulative production

$$P_{LRAC} = C_0\left(1 + g_f Q_{Pcum}\right) \qquad \textbf{Equation 6}$$

C_0 is the historic cost of production in the first time period and g_f is a growth factor that determines how rapidly production cost increases (or decreases) with cumulative production Q_{Pcum} measured from the first time period. This simple model allows scenarios of constant, increasing or decreasing production costs to be considered. I estimated g_f from official projections of costs and production technologies (NEB, 2006).

To calculate the supply price from this simple model of the production cost in the reference case I use three more parameters. One is the FLCC parameter described above. This is used to account for changes in energy prices, technology stocks and emission prices in a policy scenario. A constant k_{COP} defines the proportion of the full cost of production is accounted for by *FLCC*. The long run average cost is modified by comparing the FLCC estimate in the policy simulation with its business-as-usual value.

The second parameter is an input cost factor k_{ICF} which modifies the long-run average cost to a realistic cost trend that reflects known increases in other factors of production that are a result of short run dynamics rather than long-run resource scarcity. This is particularly useful for simulating the cost of oil and gas production, which is currently affected by significant cost increases in labour and materials.

The third parameter I add to the model is a fixed exogenous addition P_{ADD} to the cost of production. P_{ADD} is the difference between the cost of production and the market supply price and captures all other components of the price that the supply price model does not. These may include royalties, rents and company profits. The value of P_{ADD} is derived from the difference between the forecasted energy price and the estimated cost of production.

The complete model of the supply price P_s for the US and Canada is

$$P_s = \frac{1}{P_{BAU}}\left[P_{LRAC} k_{ICF}\left(\frac{FLCC - FLCC_{BAU}}{FLCC_{BAU}} k_{COP} + 1\right) + P_{ADD}\right] \qquad \textbf{Equation 7}$$

Default values for the constants in the model are listed in Appendix D. Figure 13 and Figure 14 show the production cost forecasts for oil and gas production in Canada in the business-as-usual. The market supply price forecasts are reference case forecasts of import prices to the US from the EIA Annual Energy Outlook (EIA, 2006). In this scenario, the oil and gas prices reach a peak around 2005 then decline. The oil price comes down to 40 dollars per barrel in 2010 then starts to rise after 2015, as does the price of natural gas. As mentioned in the introduction, it is important to consider alternative price scenarios because of the uncertainty in energy price forecasts.

The long-run cost of crude oil production *LRAC* is similar to *FLCC* from the CIMS model in the early years but then climbs more steeply to around 30 dollars per barrel by 2035. This is consistent with forecasts of the costs of marginal production in Canada where production from oil sands is estimated to account for ninety percent of total production by 2030 (NEB, 2006). I apply a large input cost factor k_{ICF} to the long run production cost to reflect the high costs for labour and materials in the early years and this reduces over time as the cost of production catches up with market price in this scenario. The fixed price addition P_{ADD} is roughly constant over the simulation period. The price model for Canadian natural gas production is similar although the input cost factor returns to one once the initial period of rapid output growth is over and the gap between the market price forecast and production cost is tighter.

Figure 13. Crude oil supply price model

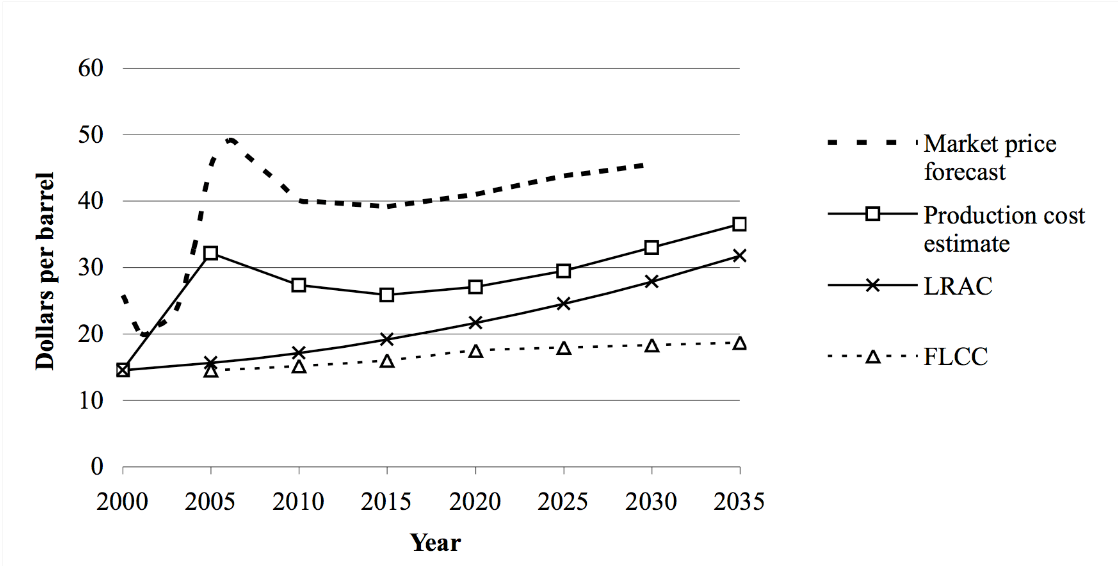
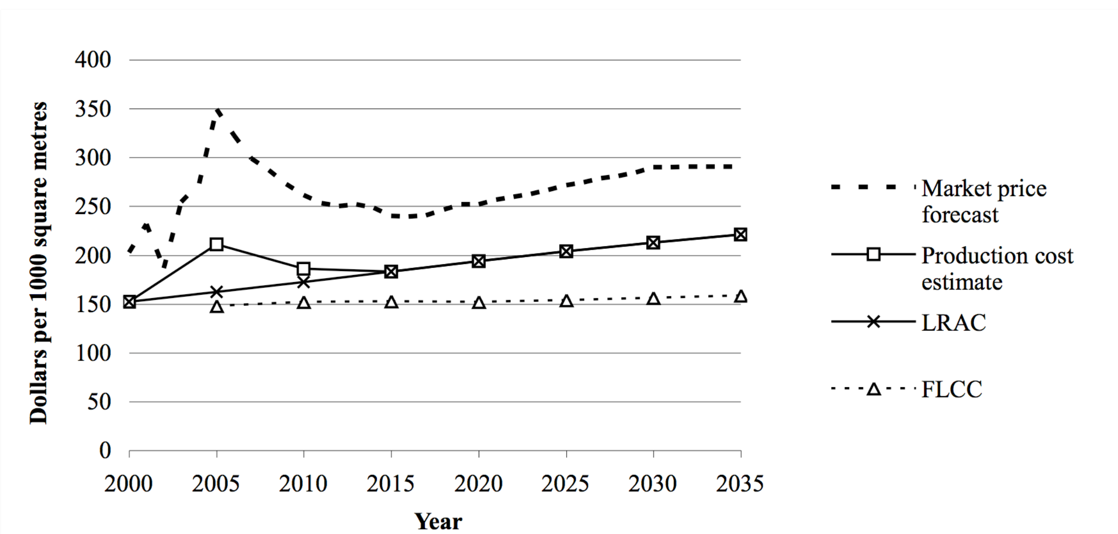


Figure 14. Natural gas supply price model



For ROW, there is no adjustment for energy or emission prices and so the supply price model simplifies to

$$P_s = \frac{1}{P_{BAU}}\left[P_{LRAC}k_{ICF} + P_{ADD}\right] \qquad \textbf{Equation 8}$$

I use this model for crude oil and natural gas supply by ROW because I expect their cost of production to increase with cumulative production. I do not consider total production by ROW or demand by other regions, only ROW supply to the US and Canada. I do not know to what extent increases in supply to North America compared to business-as-usual might affect the cost of production in ROW or how this could lead to an increase in the world price. Little data is available on crude oil production in the Middle East. Future costs of imported natural gas are also uncertain. Based on advice from oil and gas market analysts, I estimated supply cost curves for ROW supply.[26] I estimated that the cost of crude oil production in ROW in 2005 was half of the cost of conventional crude oil production in Canada (7.5 dollars per barrel). Without information on ROW production, I assumed that crude oil production costs increase slowly over time as output increases, reaching 10 dollars per barrel by 2035 in the business-as-usual scenario. This average annual increase of 1 percent is less than the annual increase in the US and Canada, which is 2.5 to 3 percent. ROW production costs are around 10 to 13 percent of the market price in the business-as-usual scenario so changes in the cost of production have a smaller effect on the supply price than in the US and Canada. ROW production costs are independent of policy, and only deviate from business-as-usual levels when the quantity produced is greater or less than the business-as-usual forecast.

The cost of natural gas imports to North America from other regions is largely determined by marine transportation cost and the cost of regasification after transfer to land. I assumed that these costs mean that ROW supply is currently more expensive than domestic production. However, I assumed that the supply price does not increase as fast

[26] Personal correspondence with market analysts of the Commodities Business Unit, National Energy Board, Calgary, AB, October 2007.

as US and Canadian production, which are limited by resource scarcity. Another explanation is that technological progress will reduce the cost of marine transportation of natural gas.

Electricity and refined petroleum products (RPP) are secondary forms of energy or energy carriers. That is, they are produced from primary forms of energy such as coal, hydropower and crude oil by conversion and refining processes. Energy conversion sectors do not experience increasing marginal costs as resource extraction sectors do, so the production cost growth factor, g_f, is zero in the supply price models for these sectors. The supply prices of electricity and RPP are largely determined by the cost of purchased primary energy as feedstock and to power the conversion processes.

Imports of electricity by the US from Mexico are insignificant in terms of quantity of energy supply. RPP imports from ROW are more significant. I use a simple supply function to model both based on a constant price elasticity of supply. ROW supply to the US $X_{1,3}$ and to Canada $X_{2,3}$ is a function of the ROW supply price

$$X_{1,3} + X_{2,3} = k_s \left(P_3\right)^{E_s} \qquad \textbf{Equation 9}$$

where E_s is the elasticity of ROW supply and k_s is total supply in the reference case. I used a low elasticity of supply for ROW so RPP and electricity imports do not respond much to increases in price. Research on RPP markets and transportation costs could produce a more realistic RPP supply function for ROW supply.

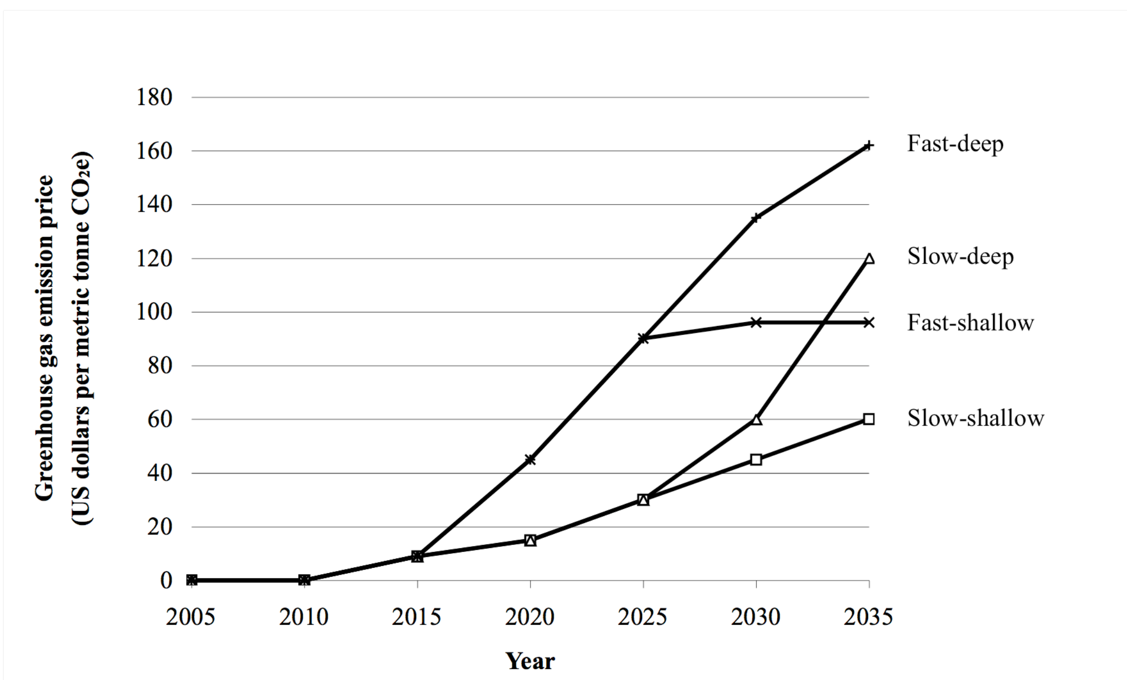
Policy scenarios

I considered four policy scenarios that represent possible carbon price paths. The carbon price, or the price of greenhouse gas emissions, is a result of government policy, which could be a carbon tax or an emission cap and permit trading system, as I described in the introduction. The four greenhouse gas price scenarios are therefore relevant for analysis of either policy mechanism because each scenario could be the result of either policy.

In all scenarios the greenhouse gas price is zero in the first two model time periods, 2005 and 2010. After 2010 the price rises. The four policy scenarios are labelled *slow-shallow*, *slow-deep*, *fast-shallow* and *fast-deep*. The emission price rises slowly in the slow-shallow and slow-deep policies, reaching 30 dollars per tonne in 2025. In the fast-shallow and fast-deep scenarios it rises faster, reaching 90 dollars in 2025. After 2025 the emission price continues to rise rapidly in the slow-deep and fast-deep scenarios, reaching 120 and 162 dollars, respectively, in 2035. In the slow-shallow and fast-shallow scenarios, it rises slower after 2025 and in the fast-shallow scenario it flattens out at 96 dollars. Figure 15 shows these four price scenarios.

The purpose of these scenarios is to simulate policies that achieve deep and shallow reductions in emissions, and to compare the effects of fast and slowly rising prices. The scenarios were developed for a previous analysis of emission reductions in Canada that forecasted a 45 percent reduction below business-as-usual in 2050 with the slow-shallow and fast-shallow policies and a 65 percent reduction with the slow-deep and fast-deep policies (Bataille et al., 2007).

Figure 15. Four greenhouse gas price scenarios



CHAPTER 5: RESULTS AND DISCUSSION

In this section, I present and discuss results of simulations using the combined US-Canada model with energy trade. There are many energy-environment policy issues that could be investigated with this model. I focus on simulations that demonstrate the model's usefulness in evaluating policies designed to reduce greenhouse gas emissions by putting an economy-wide price on emissions.

The results include:

5. Marginal abatement cost curves for the US and Canada. These describe the relationship between greenhouse gas price and emission reduction.
6. Results of a policy simulation in which the greenhouse gas price rises gradually and the effects it has on energy trade and energy prices.
7. An evaluation of the effectiveness of four alternative policy scenarios, including the effect of US climate policy on Canada's emissions.
8. Estimates of the effects of these policies on consumer energy prices.
9. An analysis of the sensitivity of results to parameters used in the trade model.

Marginal abatement costs

Policy makers and analysts are interested in the overall cost of reducing greenhouse gas emissions so that they can design effective policies that will achieve a desirable emission reduction at an acceptable cost. For economic efficiency, it is desirable to carry out the lowest cost actions to achieve a given emission target. In this situation, the marginal action (the least favourable action out of all actions taken in achieving the goal) defines the marginal cost of emission abatement. Knowing how much emission abatement opportunity exists at or below a chosen cost level and knowing the maximum cost level required to meet a chosen emission reduction target is important for policy design.

The marginal abatement cost curve can be inferred from the CIMS model by running repeated simulations with different levels of carbon price and recording the total reduction in emissions resulting from each carbon price. I produced marginal abatement cost curves (Figure 16) by assuming a constant emission price starting in 2010 in both the US and Canada and continuing at the same level in subsequent years. The three curves in the figure are the results from different model time periods. In 2015, after 5 years of the emission price, the emission reduction from the business-as-usual scenario is less than after 10 years (in 2020) and 20 years (in 2030). The differences in the level of emission reduction at a given price level reflect the time dependence of emission abatement opportunity.

Figure 16. Marginal abatement cost curves – US

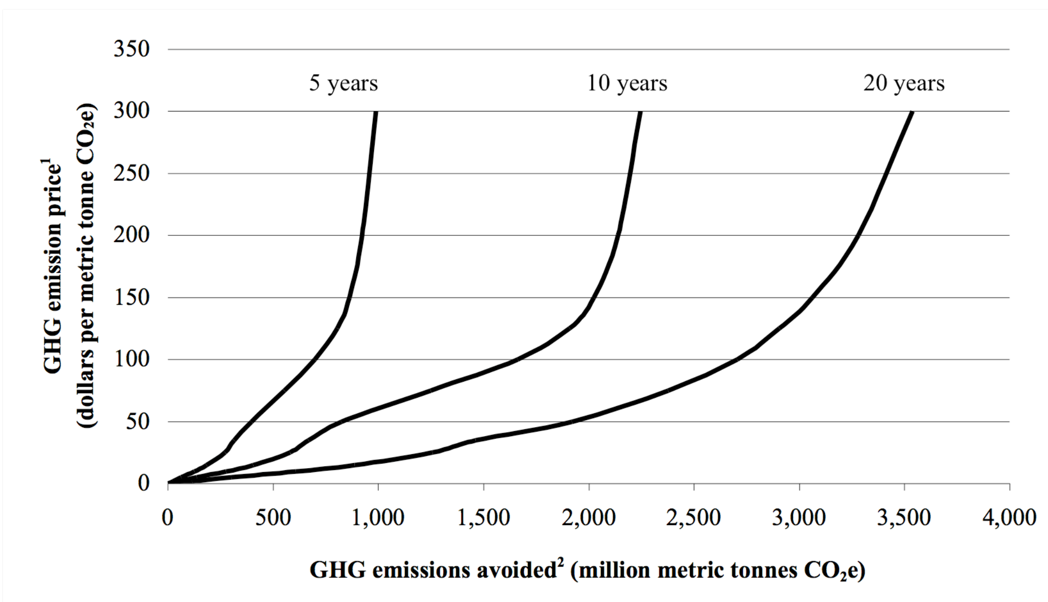


Figure notes:

1. Greenhouse gas emission price. In each simulation a constant price was applied starting in 2010.
2. The difference between greenhouse gas emissions in the business-as-usual scenario and in the policy scenario in 2015, 2020 and 2030 (5, 10 and 20 years after the start of the policy).

A recent study by the business consulting firm McKinsey estimated that 3.0 to 4.5 billion metric tonnes of greenhouse gas emissions could be avoided in the US in 2030 at a cost of 50 dollars per ton or less (Creyts et al., 2007). Using CIMS with my model structure, assumptions and parameters, the amount is 1.7 billion metric tonnes. This is the point in Figure 16 where the 20-year marginal abatement cost curve intersects the 50-dollar GHG price gridline.

Other results published by academic research groups are comparable with the abatement costs estimated by my research. Sands used a computable general equilibrium model called SGM to produce marginal abatement cost curves for the US (Sands, 2004). Like CIMS, the SGM model simulates capital stock adjustment over time, so it is able to produce marginal abatement cost curves for the short and long run. The SGM results for simulations of a constant carbon-price over the long run (20 years) are similar to the CIMS results. Figure 17 compares marginal abatement cost curves from the SGM model with those from the US and Canada CIMS models used in this research. In this figure avoided emissions are expressed as a percentage of business-as-usual emissions.

Figure 17. Comparison of marginal abatement cost curves

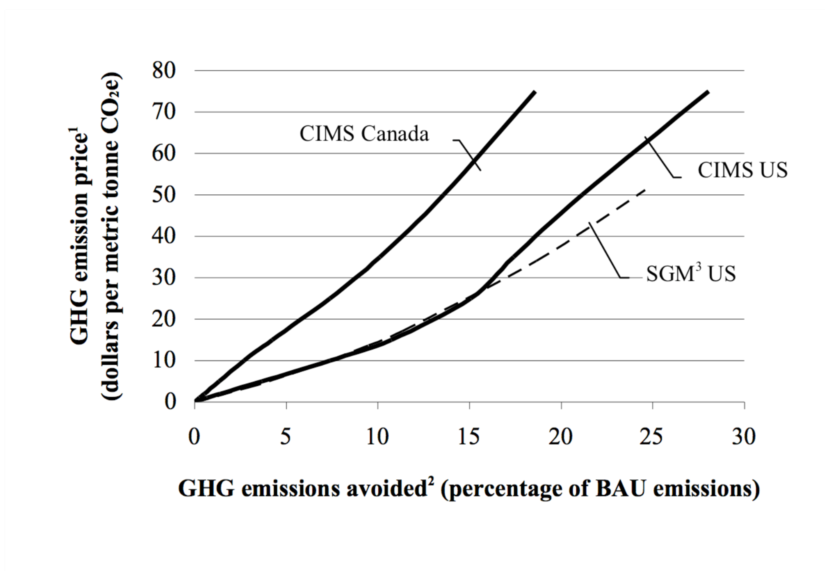


Figure notes:

1. Greenhouse gas emission price. Same in all time periods after start of policy.
2. Percentage of business-as-usual emissions avoided in 2030, 20 years after start of policy.
3. Results from the Second Generation Model (Sands, 2004).

Comparing the marginal abatement cost curves for Canada and the US, a greater percentage of business-as-usual emissions are avoidable in the US than in Canada, with the same emission price (in US dollars). For emission prices below 25 dollars per tonne, the percentage avoided in the US is over twice the percentage avoided in Canada. This is explained by the large amount of low cost emission abatement opportunity that exists in the US electricity generation sector compared to Canada.

The differences between the McKinsey results and those from CIMS are likely a result of the different methodology employed. The McKinsey study is a bottom-up analysis of abatement opportunities in all sectors. It uses an accounting method to quantify the total emission reduction potential of the opportunities identified and includes only financial costs in estimating the cost of abatement. A large proportion of the opportunities quantified are estimated to be profitable or have zero marginal cost.[27] This type of approach ignores risk and quality differences in technologies, and decision-making behaviour that is determined by other factors. The CIMS model includes estimates of intangible costs associated with some technologies and has a more realistic model of decision-making behaviour.

Because the McKinsey study does not appear to account for technological progress and the likely rate of adoption of technologies in the business-as-usual scenario, it is not clear how much of the total emission abatement potential qualifies as a reduction below business-as-usual that could be achieved by policy.

Finally, the study also ignores adjustments in the economy, such as changes in energy demand and prices that are likely to occur in an emission abatement scenario. Probably for these reasons, the estimates of total abatement potential by McKinsey are higher than the forecasts from simulation models such as CIMS and SGM, which have realistic models of behaviour and simulate the likely response of the economy to a climate policy.

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[27] According to the report "almost 40 percent of abatement could be achieved at negative marginal costs, meaning that investing in these options would generate positive economic returns over their lifecycle" (McKinsey, 2007, pp. xii).

Energy trade in a policy scenario

In this section, I present the results of simulating a policy scenario where the greenhouse gas price in Canada follows the slow-shallow path and the greenhouse gas price in the US is zero. It is not a likely scenario because the US will most probably implement some kind of greenhouse gas policy instrument over the next 25 years. Some jurisdictions already have.[28] Nevertheless, this is an interesting scenario to analyse because it demonstrates how the trade model responds to the effects of an isolated greenhouse gas price in one country (Canada).

The energy trade model is calibrated to the business-as-usual scenario and prices are normalised to business-as-usual prices. Table 12 shows the trade solution for energy prices in 2030 in the policy scenario. The energy supply price index P_{CA} is greater than one for all energy commodities as a result of increases in the costs of energy production in Canada due to the emission price. The energy supply prices in the US and the rest-of-the-world, P_{US} and P_{ROW}, are hardly affected. The effect on the energy supply price in Canada is greatest for electricity – a 13 percent increase – and least for refined petroleum products – a 3 percent increase.

PA_{US} and PA_{CA} are the composite energy prices in the US and Canada. They represent the average price of energy consumed in each region and are a function of the supply prices in all regions. Because most electricity is produced domestically the composite energy price for electricity is the same as the domestic supply price. Consumers in Canada experience a 13 percent increase in electricity prices in this scenario. The electricity price in the US is unaffected by the policy in Canada.

[28] US climate policy was initially driven by states such as California. Now initiatives such as The Western Climate Initiative (WCI), the Regional Green House Gas Initiative (RGGI) and the Midwestern Regional Greenhouse Gas Reduction Accord (MRGGRA) are co-ordinating the efforts of many states. Several Federal bills that include greenhouse gas emission price mechanisms are also before Congress.

Table 12. Energy prices in 2030 in a simulation with a climate policy in Canada only

Normalised prices[1]	Electricity	Refined petroleum products	Natural gas	Crude oil
P_{US}	1.00	1.01	1.00	1.01
P_{CA}	1.13	1.03	1.08	1.06
P_{ROW}	1.00	1.00	1.00	1.00
PA_{US}	1.00	1.01	1.01	1.02
PA_{CA}	1.13	1.03	1.04	1.03

Table notes:

1. P_{US}, P_{CA} and P_{ROW} are energy supply prices normalised to the business-as-usual scenario for US, Canada and rest-of-the-world supply. PA_{US} and PA_{CA} are composite energy prices in the US and Canada.
2. All figures are model results from a slow-shallow emission price scenario simulation where the greenhouse gas price rises from zero in 2010 to 45 dollars per metric tonne CO_2e in 2030.

For commodities where a proportion of demand is met by imports, the prices are influenced by changes in the price of imports. For example, the composite price of natural gas in Canada PA_{CA} is 4 percent higher than business-as-usual, even though the supply price of natural gas in Canada P_{CA} is 8 percent higher. This is because a proportion of Canada's natural gas supply comes from the US and the rest-of-the-world, neither of which experience the emission price policy. The composite prices of crude oil, natural gas and refined petroleum products are slightly higher in the US. This is due to increases in the price of Canadian energy supplied to the US.

The composite energy price is not the same as the price paid by consumers. Consumers of refined petroleum products and natural gas also pay the price for their emissions from the use of these fuels, which is collected via a fuel tax. This means that increases in the prices of natural gas and refined petroleum products are more than those reflected in the composite energy prices shown in this table for most end-users. I calculate the full price increases experienced by end users later in this chapter.

Table 13 shows the energy trade outcome. The six trade flows represent the energy goods supplied to the US and Canada, by the three supply regions, the US, Canada and rest-of-the-world (ROW). $X_{US\text{-}ROW}$ is the supply of the US by the rest of the world, and $X_{CA\text{-}CA}$ is Canadian production for domestic consumption, and so on. Consumption by the rest-of-the-world is not included in the trade model. The sub-totals for Canada and the US indicate total supply (and demand) in each country.

Table 13. Changes in energy supply and demand in 2030 with a climate policy in Canada only

Traded goods	Electricity (petajoules) BAU	Electricity (petajoules) Policy	Refined petroleum products (petajoules) BAU	Refined petroleum products (petajoules) Policy	Natural gas (petajoules) BAU	Natural gas (petajoules) Policy	Crude oil (petajoules) BAU	Crude oil (petajoules) Policy
$X_{US\text{-}US}$	15,465	15,508	52,751	52,771	23,624	24,100	10,341	10,897
$X_{US\text{-}CA}$	84	60	1,861	1,773	3,164	2,489	11,665	9,516
$X_{US\text{-}ROW}$	13	13	8,242	8,266	6,965	7,159	19,491	21,152
Sub-total	15,562	15,580	62,854	62,811	33,754	33,748	41,497	41,565
$X_{CA\text{-}US}$	59	84	281	276	206	216	61	64
$X_{CA\text{-}CA}$	2,132	2,163	3,728	3,486	2,248	1,812	2,239	1,826
$X_{CA\text{-}ROW}$	0	0	70	69	1,858	1,957	1,927	2,092
Sub-total	2,190	2,247	4,078	3,830	4,312	3,984	4,227	3,982

Table notes:
1. The six variables denoted $X_{AA\text{-}BB}$ are quantities of energy supplied by one country (BB) to another country (AA) in physical units.
2. BAU results are from the business-as-usual simulation.
3. Policy results are from a slow-shallow emission price scenario simulation where the greenhouse gas price rises from zero in 2010 to 45 dollars per metric tonne CO_2e in 2030.

Looking at the electricity trade results in the first two columns, total demand in Canada is higher in the policy scenario, but the increase in domestic production (the sum of $X_{CA\text{-}CA}$ and $X_{US\text{-}CA}$) only accounts for a part of the increase in demand. Most is met by an adjustment in imports and exports. Canadian exports to the US are lower and imports from the US are higher. How realistic is this result? Most of Canada's exports to the US are by eastern provinces where electricity is generated by hydroelectric facilities. The cost of production from these facilities is low and unaffected by greenhouse gas prices so it is unlikely that the supply price would change. The increase in imports is plausible if the Canadian market price is higher, although political concerns also tend to determine the level of imports.

Refined petroleum products supply and demand is not affected much by the policy. Canadian production is lower due to a drop in domestic demand and a reduction in exports to the US.

Natural gas supply and demand are noticeably affected. Total demand in Canada is lower because of the increased price, and imports from the rest of the world $X_{CA\text{-}ROW}$ have displaced some domestic production, but the impact on exports to the US $X_{US\text{-}CA}$ is greater than both these effects combined with the result that natural gas production in Canada is 20 percent less than business-as-usual. The US compensates by increasing domestic production and imports from the rest of the world.

Crude oil follows a similar pattern to natural gas supply and demand. The higher Canadian supply price causes substitution in both countries of Canadian production with US production and higher imports from the rest of the world. The result is that Canadian production is 18 percent lower than business-as-usual. How likely is this result? It depends largely on how well this trade model represents crude oil supply and demand. Crude oil markets are complex and determined by many factors other than costs of production, including government intervention and geo-political issues. A simple model such as this one cannot adequately represent the dynamics involved.

One criticism of this model is that the supply price in Canada influences the average price of crude oil. Canada is a price-taker in a world market because oil can be transported long distances at low cost and changes in Canada's output are too small to shift the world price (NEB, 2007). This is not likely to change much even when Canada's output grows. To solve this problem, the trade model would have to be extended to include global crude oil supply and demand. However, the problem does not have a big impact in results because the price increase is relatively small (the adjustment in total crude oil demand is only 0.3 percent in this simulation). Most of the model results of interest to policy-makers, such as the changes to Canadian crude oil production, are determined by changes in production costs. Without the increase in crude oil price, Canadian production would be slightly lower in the policy scenario.

A bigger criticism of the model is the assumption that an increase in the cost of crude oil production causes an increase in supply price that would affect output levels. In the model, the supply price is determined by adding a fixed amount to the adjusted production cost (P_{ADD} in Equation 7). This amount represents the economic rent that producers earn or that is transferred to the government by royalty payments. In reality, increases in the cost of production as a result of climate policy might be offset by reductions in royalties. How much scope or political will there is to prevent growth in oil sands output from being curtailed by environmental policy is hard to predict. The model would certainly benefit from a thorough analysis of how changes in production costs in Canada may or may not translate into adjustments in output.

I also looked at the change in total expenditure on energy commodities. This is interesting to policy analysts because an increase in total energy expenditure (quantity multiplied by price) is a measure of the impact of the policy on consumers and the economy. Table 14 shows total expenditure Y in the trade model, normalised to the business-as-usual. Expenditure on electricity in Canada is 23 percent higher in this policy scenario. This is because electricity price and demand are higher in the policy scenario. Electricity demand increases despite the price increase because electricity is still a lower cost alternative to fossil fuels in many applications, when emission costs are included.

However, it is important to understand what happens to the revenue from an emission tax. In this research, I have not considered how the government redistributes the revenue raised by a tax. In my model the revenue simply disappears and there is no change in net income or consumption. In reality some consumers may be better off as a result of the policy. Others will experience a net increase in expenditure on energy.

Total expenditure on energy supply is not so meaningful for other energy commodities because it does not include the emission taxes paid by consumers who use fuels, and also because of the crude oil price adjustment which may not be realistic, as previously discussed. However, it can be seen that US expenditure on energy is hardly affected by the Canadian climate policy if the crude oil adjustment is ignored.

Table 14. Changes in total expenditure on energy with a climate policy in Canada only

Total expenditure[1]	Electricity	Refined petroleum products	Natural gas	Crude oil
Y_{US}	1.00	1.01	1.01	1.02
Y_{CA}	1.23	0.94	0.94	0.95

Table notes:

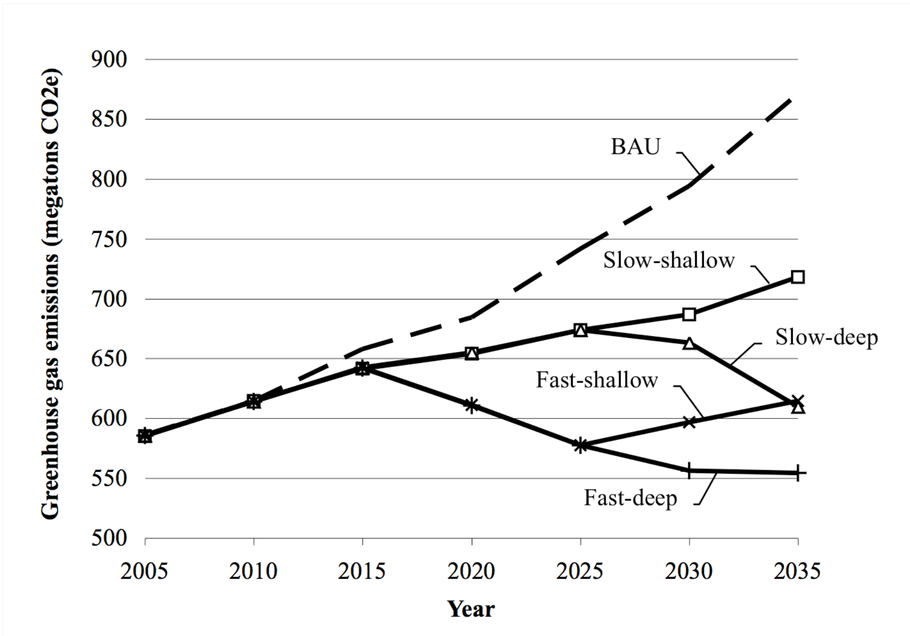
1. Y_{US} and Y_{CA} are total expenditure in the US and Canada on each energy commodity normalised to business-as-usual expenditure. These results do not include charges for end-use emissions that are paid by consumers of refined petroleum products and natural gas.
2. All figures are model results are from a slow-shallow emission price scenario simulation where the greenhouse gas price rises from zero in 2010 to 45 dollars per metric tonne CO_2e in 2030.

Emissions avoided due to policy

Now I present and discuss forecasts of greenhouse gas emissions and the amount of emissions avoided in the four policy scenarios that I considered. Figure 18 shows the emission forecasts from simulations where the greenhouse gas emission price in Canada and the US is identical and follows the four emission price scenarios, slow-shallow, slow-deep, fast-shallow and fast-deep. As expected, emissions in 2015 and beyond are lower in the policy scenarios than in the business-as-usual. The amount by which emissions reduce and the rate of change are determined by the emission price in the policy (refer back to Figure 15 to compare these emission forecasts with the emission price paths of each policy scenario).

In the slow-shallow policy scenario, which is a slowly rising emission price that reaches 60 dollars per tonne by the end of the simulation, growth in emissions is slower than business-as-usual but total emissions continue to increase. In the slow-deep policy scenario, emissions begin to reduce after 2025 when the emission price starts to rise quickly to 120 dollars per tonne. In the fast-shallow and fast-deep scenarios emissions decline significantly after 2015. In the fast-shallow scenario, where the emission price rises quickly but does not exceed 100 dollars per tonne, emissions begin to grow again after 2025 and emissions in 2035 are about the same as in the slow-deep scenario. Only in the fast-deep scenario do emissions reduce to a level below the 2005 level. These results are useful because policy makers want to know what emission prices are required and the appropriate timing to achieve greenhouse gas emission targets.

Figure 18. Forecasted emissions in Canada in four policy scenarios



Climate policy goals are usually expressed as a reduction in absolute emissions, either below business-as-usual levels or compared to a historical level. However, greenhouse gases are stock pollutants and have long-term impacts on climate change.[29] This means that cumulative emissions over the life of the policy are as important as the future level of emissions. Table 15 summarises the effectiveness of the four policy scenarios by showing both the percent reduction in emissions in 2030 and the reduction in cumulative emissions over the simulation timeframe. The table also shows the emission reductions that occur in the US. These results show that the fast emission price paths, where the price rapidly increases after 2015, have a greater impact on cumulative emissions avoided than the slow paths. The fast shallow price path, which achieves the same emission level by 2035 as the slow-deep path, avoids one billion additional tonnes

[29] A stock atmospheric pollutant has a long residence time in the atmosphere and therefore accumulates over time with long-lasting impacts.

of emissions that is not avoided by the slow-deep path where the price increases ten years later.

Table 15. Forecasted emission reductions for identical US-Canada climate policy scenarios

	Canada		US	
Policy scenario	**Reduction in forecasted emissions in 2030 with policy (percent)**	**Cumulative emissions avoided by 2035 with policy (billion metric tonnes CO_2e)**	**Reduction in forecasted emissions in 2030 with policy (percent)**	**Cumulative emissions avoided by 2035 with policy (billion metric tonnes CO_2e)**
Slow-shallow	12	1.2	15	16
Slow-deep	14	1.5	16	18
Fast-shallow	23	2.5	26	27
Fast-deep	28	2.8	28	29

Next I consider a scenario where the US has no climate policy, to see what difference this makes to the results. Table 16 shows the same results as Table 15 but from simulations where only Canada has the climate policy – the emission price is zero in the US. In each policy scenario, emissions are reduced more in Canada when the US does not have an equivalent climate policy (12 percent more on average). This is a direct result of changes in energy supply and demand in the trade model. When the US has a climate policy, its demand for imports of energy, especially for natural gas, is higher and some of that demand is met by Canada. When the US does not have a policy and Canada does, energy imports by the US from Canada are replaced by US domestic production and imports from the rest-of-the-world.

As expected, there are no emission reductions in the US when there is no policy. Indeed the emission abatement figures in Table 16 are negative for the US, indicating that when there is a policy in Canada only, emissions are greater in the US than in the business-as-usual. This is due to the phenomenon known as *leakage* (Felder and Rutherford, 1993). Some of the emission reductions intended by the policy in Canada have leaked to the US and the rest of the world as a result of the changes in energy production and trade. For example, in the slow-shallow scenario, of the 1.5 billion tonnes of emissions reduced in Canada, 400 million tonnes have leaked to the US. I found that the “leakage rate” to the US in the model is about one quarter of emissions reduced in Canada for most policy scenarios. In addition to this leakage, there is leakage to the rest-of-the-world that I did not quantify.

Table 16. Forecasted emission reductions for Canada-only climate policy scenarios

	Canada		US	
Policy scenario	**Reduction in forecasted emissions in 2030 with policy (percent)**	**Cumulative emissions avoided by 2035 with policy (billion metric tonnes CO_2e)**	**Reduction in forecasted emissions in 2030 with policy (percent)**	**Cumulative emissions avoided by 2035 with policy (billion metric tonnes CO_2e)**
Slow-shallow	14	1.5	0	-0.4
Slow-deep	16	2.0	0	-0.6
Fast-shallow	25	2.9	-1	-0.9
Fast-deep	30	3.3	-1	-1.0

Increases in energy prices

In addition to cost and effectiveness, policy makers also want to know whether policies are politically acceptable. One important factor that determines political acceptability is the increase in energy prices that consumers are expected to face. Sharp increases in prices in the short term are very unpopular, especially if energy prices increased in previous years. Table 17 shows the maximum price increases for three important energy commodities from each policy scenario simulation. The natural gas price experiences the biggest increases, in the range 50 to 120 percent depending on the policy scenario. The maximum gasoline price increases are 30 to 80 percent. Natural gas and gasoline price increases are the same in both countries. The electricity price increases 20 to 40 percent in Canada and 30 to 50 percent in the US. The highest prices occur in the fast-deep and slow-deep simulations where the emission price exceeds 100 dollars per tonne. Although these increases are quite significant, none occur in the early years of the policy scenarios. The maximum prices occur in the year of highest emission price, which for most simulations is 2035. The impact of higher prices also depends on what happens to the revenue generated by an emission price. If the revenue is reimbursed to consumers then higher prices may be politically acceptable. If the revenue is shared by producers within the energy sector, then price increases may be lower.

Table 17. Forecasted maximum energy price increases in Canada and the US

	Canada			US		
Policy scenario	**Electricity**	**Natural gas**[2]	**Gasoline**[2]	**Electricity**	**Natural gas**[2]	**Gasoline**[2]
Slow-shallow	1.2	1.5	1.3	1.3	1.5	1.3
Slow-deep	1.4	1.9	1.6	1.5	1.9	1.6
Fast-shallow	1.3	1.8	1.5	1.5	1.8	1.5
Fast-deep	1.4	2.2	1.8	1.5	2.2	1.8

Table Notes:

1. The maximum price index is the highest value of the market price in the simulation timeframe (2005 to 2035) divided by the business-as-usual price.
2. The prices of gasoline and natural gas include the charge on final consumers for their end-use emissions.

Sensitivity analysis

I carried out a simple analysis to investigate the sensitivity of simulation results to parameters used in the trade model. I did not carry out an analysis of uncertainty in the sector flow models. Because of the complexity of these models and the large amount of data used, this would be a challenging and time-consuming undertaking. Improvements in the speed of sector flow model calculation would make it easier to evaluate sensitivity and uncertainty in these models. This would be a valuable exercise because it would allow research effort to be directed to the components of the models that affect uncertainty most.

Because of the duration of simulations I was limited to 35 simulation experiments for sensitivity analysis. I did a simple sensitivity analysis where I investigated the relative variation of simulation results with respect to changes in selected model parameters and calculated the normalized sensitivity in the form of an elasticity (Morgan and Henrion, 2003). This type of sensitivity analysis ignores the relative uncertainty in each input parameter and also ignores the fact that the effect of one parameter may depend on the values of other parameters. A thorough parametric sensitivity analysis was not possible given the practical constraint on the number of simulations.

By running separate simulations modifying one parameter at a time I determined the variation in results caused by each parameter. I focussed the analysis on the energy trade model parameters that I believed to be least certain and most likely to influence results. These were: the Armington elasticity of substitution σ of each energy good (4 parameters), the production cost growth factor g in crude oil and natural gas production by each country (6 parameters), the initial production cost parameter C_0 for natural gas and crude oil production by the rest-of-the-world (2 parameters), and the elasticity of supply E_s for electricity and refined petroleum products production by the rest-of-the-world (2 parameters).

For the sensitivity analysis, I used a policy scenario with an identical greenhouse gas price in the US and Canada. I analysed the sensitivity of various model results to the chosen parameters. Figure 19 shows the sensitivity of the forecast of greenhouse gas emission in Canada in 2035 to the five parameters that produced the greatest variation in the result. All other energy trade model parameters that I tested had a smaller effect. The horizontal bars in the figure show the variation in the simulation result from the nominal value of 220 million metric tonnes of CO_2e. The values to either side of the bars indicate the alternative values of each parameter that produced the minimum and maximum values of the result.

Figure 19. Sensitivity of the forecast of emissions avoided to trade model parameters

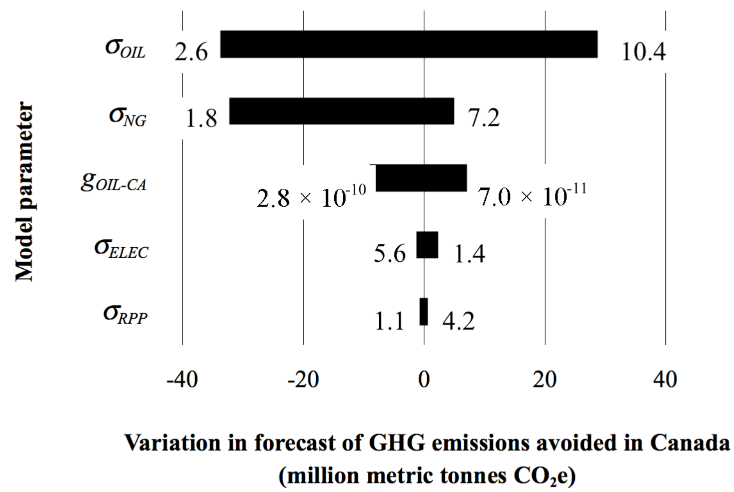


Figure notes:

1. Separate simulations were carried out to investigate the effect of changes in trade model parameters. Each parameter was halved (× 0.5) and doubled (× 2). The graph shows the sensitivity of one simulation result to five trade model parameters. σ_{OIL}, σ_{NG}, σ_{ELEC} and σ_{RPP} are the Armington elasticities of substitution for crude oil, natural gas, electricity and refined petroleum products, respectively. $g_{OIL\text{-}CA}$ is the production cost growth rate parameter for crude oil production in Canada. The figures to the left and right of each bar are the values of the model parameter that produced the minimum and maximum result.
2. The slow-deep policy scenario was used for this sensitivity analysis. The simulation result analysed is the amount of greenhouse gas emissions avoided in 2035 as a result of the policy (compared to the business-as-usual scenario). The bar in the figure represents a range of simulation results for variations in each trade model parameter between the minimum and maximum values shown. The default forecast of emissions avoided in 2035 in this scenario is 220 million metric tonnes CO_2e.

The bar at the top is the variation caused by changes in the Armington elasticity of substitution for crude oil supply. An elasticity of 2.6 produces a forecast of 190 million metric tonnes of emissions in 2035 and an elasticity of 10.4 produces a forecast of 250 million metric tonnes. The explanation for this result is that a higher elasticity means more substitution among different sources of supply when prices change. When more substitution occurs Canada and the US produce less and imports from the rest-of-the world are higher. This results in lower emissions from energy supply sectors in Canada. The variation amounts to plus and minus 14 percent of the default forecast.

Although the largest variation is caused by changes in the Armington elasticity of crude oil substitution, the result is also sensitive to the Armington elasticity for natural gas supply σ_{NG} and somewhat sensitive to the production cost growth factor for crude oil production in Canada $g_{OIL\text{-}CA}$. The production cost growth factor determines the increase in production costs when cumulative production exceeds business-as-usual.

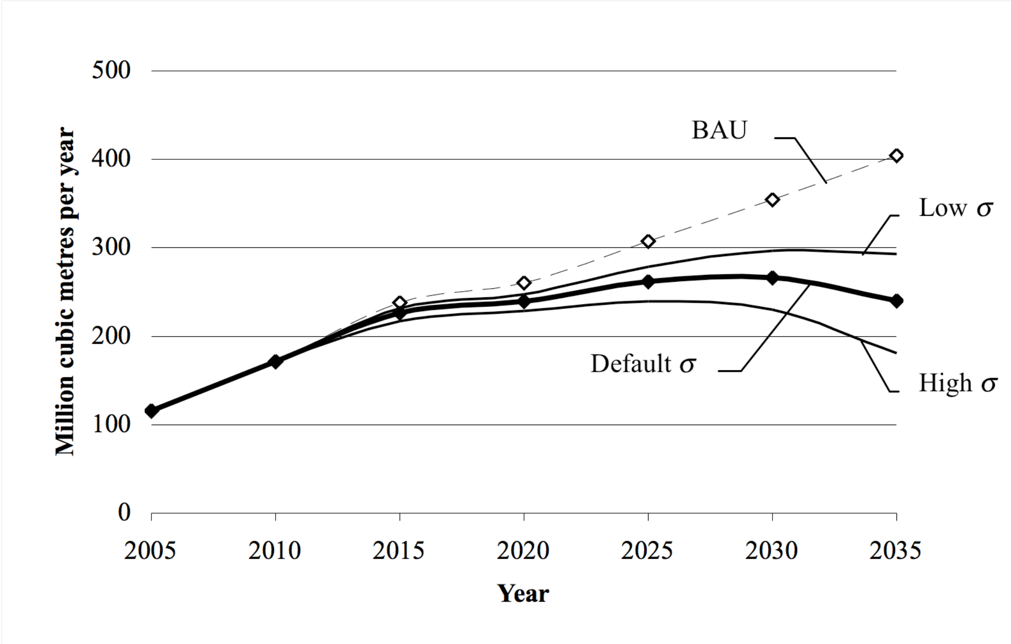
Although most simulation results are sensitive to the Armington elasticities for crude oil and natural gas, the results are not always the same. For example, the US emission forecast is more sensitive to the Armington elasticity of natural gas supply than to that of crude oil. This is due to the critical role that natural gas plays in displacing coal fired electricity generation in the US in policy simulations.

The energy trade model results that varied most during the sensitivity analysis were the production and export of natural gas and crude oil by Canada, and as well as US imports of natural gas from the rest-of-the-world. These results tended to vary between half and one-and-a-half times the quantities in the business-as-usual scenario. In one of the sensitivity experiments, natural gas production in Canada reduced to 10 percent of the forecast. This occurred when the Armington elasticity of natural gas supply was at its extreme value of 7.2.

To illustrate the uncertainty in these model results, Figure 20 shows forecasts of crude oil production in Canada for the high, low and default values of the Armington elasticity σ. This confirms a well-known problem with Armington trade models. Not only are values of the Armington elasticity σ highly uncertain, the results produced by Armington trade models are highly dependent on these values.

The model is likely to be sensitive to many other assumptions including alternative energy price forecasts, which were not considered here. A more holistic sensitivity analysis could be carried out to determine the parameters or components of the model that results are most sensitive to. It may even be possible to estimate the probable uncertainty in results. Before attempting any serious sensitivity analysis it is necessary to improve the computational speed of the model.

Figure 20. Sensitivity of Canadian crude oil production forecast to the elasticity of substitution



Notes:
1. These are results from a policy scenario simulation with an identical slow-deep GHG emission price in the US and Canada.

Discussion

By adopting the CIMS modelling framework for the sector models, the model takes account of the energy, emission and cost characteristics of technologies and has a realistic method of simulating technological progress by accounting for capital stock turnover, producer and consumer decision-making and learning-by-doing. However, the model does not possess all the requirements of an ideal climate policy simulation model. It does not model changes to supply, demand and prices of goods other than energy commodities, and it does not include a macroeconomic model that can take account of likely changes to output and final demand in sectors other than energy supply. The sector models also have a number of shortcomings. A full list of recommended model improvements is included in Appendix E for future research purposes. Addressing these would improve confidence in the results.

Deciding how to make further progress at this point demands a holistic view of the available options. One option is to continue expanding the model developed here. The macroeconomic feedback method used in the existing CIMS model could be incorporated into the computational framework that manages energy supply and demand relatively easily. It would merely require further equations and unknowns to be added to the model and additional links to the sector models.

The trade model used for energy commodities is equally capable of simulating international trade in other goods. This would make sense for trade in some commodities that are energy intense to produce but not significantly affected by commodity prices other than energy. Examples include industrial minerals, pulp, paper, steel, other metals and some commodity chemicals. Sector output in these industries could be linked to a trade model identical to the energy trade model used in this research. However, to build a more complete model of supply and demand in all traded goods requires a model of all commodity flows between sectors (an input-output model) for each country. This would be necessary to simulate possible changes in Canada's trade in intermediate goods as a result of climate policies. This is an issue that may determine the political acceptability of Canadian climate policies.

The problem with extending the existing model – incrementally or by linking it dynamically to a computable general-equilibrium (CGE) model – is that the resulting integrated model would be even larger and more complex than the present model. The end result would be a rather monolithic model that includes a complete model of the macro-economy (a top down model) and detailed models of technologies and decision-making behaviour in all sectors (a bottom-up model). As well as demanding a large amount of computational resources, large complex models are more difficult to comprehend and maintain.

An alternative to this approach would be to maintain two separate models that can be operated in parallel. The top-down model (an existing CGE model could be used) would simulate the macro-economy and provide information on macroeconomic feedbacks that could be passed to a bottom-up model. The bottom-up model would simulate sector energy use and emissions and changes to production costs that occur when a climate policy is simulated. These effects could, in turn, be passed back to the top-down model to verify if the macroeconomic adjustments are valid. One question with this approach is where to draw the dividing line between the bottom-up model's capabilities and the top-down model. Some degree of overlap may be useful. This research has shown that good models of energy supply and energy trade are useful capabilities, at least for Canadian policy analysis, and so it might be advantageous to maintain these in the bottom-up model.

Whatever the modelling approach, in the long-run the reliability and usefulness of complex economic forecasting models depends a lot on the institutional context in which they are developed and maintained. Whilst it is accepted that economic forecasting is not an exact science and that there is a benefit in independent research efforts, transparency and knowledge sharing between research groups is encouraged. Improvements are identified through testing, comparison and critique of models by peer groups. The application of expert knowledge, especially specialist sector expertise, also improves confidence in models. Finally, retrospective review of model results is a good way to evaluate the strengths and weaknesses in the model and to direct research priorities. As we now have data on actual energy use and emissions in 2005, it would be beneficial to review the variation between the model and reality.

CHAPTER 6: CONCLUSION

The objective of this research is to improve the analysis of Canadian and US climate policy by simulating the combined energy supply and demand system of both countries. I built simulation models of energy use in both countries and connected them to models of energy supply using a model of energy trade between the US, Canada and the rest of the world. The integrated model allows simulations of any number of policy scenarios, including Canadian and US policies or combinations of both.

The simulation results demonstrate that the model is able to provide useful information on the cost, effectiveness and economic impacts of climate policies. The results showed that an integrated model of energy supply and demand between multiple regions can take account of changes in energy supply and trade, and is especially useful in the case of Canadian policy analysis. The model provided information on changes in energy prices and the leakage of emission reductions to other countries. These results are important to climate policy analysis because they allow the political acceptability of climate policies to be evaluated. The ability to simulate US policy allows Canadian policy makers to determine the benefits of policy co-ordination with the US.

By using the CIMS modelling framework for the sector models, the model takes account of the energy, emission and cost characteristics of technologies and has a realistic method of simulating technological progress by accounting for capital stock turnover, producer and consumer decision-making and learning-by-doing. This project has extended these existing capabilities by building a sophisticated model of energy supply and demand that overcomes many of the limitations of the existing CIMS model. The model can now simulate equilibrium in four or more energy markets, energy consumption in energy supply sectors, and international trade. The model is therefore capable of simulating climate policy in multiple countries or global regions.

However, uncertainty in the model results is not known and the model has a series of shortcomings that could be addressed. A simple sensitivity analysis showed that the emission forecasts are sensitive to assumptions about energy trade. The model's forecasts of how Canada's energy exports may change as a result of climate policy are especially sensitive to these assumptions. Reviewing and improving the energy trade and supply models is therefore a priority.

Despite the shortcomings in the current model, this research is a step towards the integration of bottom-up technology models and top-down macroeconomic models and towards a model that meets the requirements of simulation models for climate policy analysis outlined in the introduction.

APPENDICES

Appendix A: Model calibration results

Table 18. Year 2000 calibration results by sector – US model

Sector	Electricity	Natural gas[2]	Refined petroleum products[3]	Coal	Other fuels[4]	Greenhouse gas emissions (million metric tonnes CO_2e)
	Energy consumption (petajoules)					
Transportation						
Reference data	80	7	28,533	-	-	1,840
Model data	34	38	28,096	-	-	2,023
Variance	-46	30	-438	-	-	183
Commercial						
Reference data	4,177	3,584	668	96	-	441
Model data	4,177	3,499	659	0	-	230
Variance	0	-85	-8	-96	-	-211
Residential						
Reference data	4,293	5,977	1,003	13	-	400
Model data	4,333	5,981	906	0	-	374
Variance	40	4	-97	-13	-	-26
Chemicals						
Reference data	580	1,980	61	369	1,006	311
Model data	585	1,927	60	358	997	130
Variance	5	-53	-1	-10	9	-181
Industrial minerals						
Reference data	146	458	40	313	113	91
Model data	146	458	40	314	112	112
Variance	0	0	0	0	1	21
Iron and steel						
Reference data	246	521	26	722	-	144
Model data	171	487	26	710	-	84
Variance	-75	-34	0	-11	-	-60

Sector	Energy consumption (petajoules)					Greenhouse gas emissions (million metric tonnes CO_2e)
	Electricity	Natural gas[2]	Refined petroleum products[3]	Coal	Other fuels[4]	
Metals						
Reference data	291	264	112	29	-	69
Model data	409	140	86	34	-	28
Variance	119	-123	-26	5	-	-41
Mining (excluding coal mining)						
Reference data	-	-	-	-	-	-
Model data	299	30	257	85	-	17
Variance	-	-	-	-	-	-
Other manufacturing						
Reference data	1,349	1,708	109	275	598	121
Model data	1,368	1,720	110	277	600	117
Variance	19	12	1	3	3	-5
Pulp and paper						
Reference data[1]	237	532	119	251	1,342	102
Model data	241	513	120	252	1,128	55
Variance	4	-19	1	1	-214	-48
Agriculture						
Reference data	183	352	615	-	-	495
Model data	-	-	-	-	-	-
Variance	-	-	-	-	-	-
Construction						
Reference data	237	730	23	-	-	16
Model data	-	-	-	-	-	-
Variance	-	-	-	-	-	-
Petroleum refining						
Reference data	121	943	652	55	1,510	305
Model data	115	974	635	55	1,509	186
Variance	-6	31	-17	1	0	-119
Natural gas production						
Reference data	-	1,924	-	-	-	258
Model data	140	2,376	42	-	-	299
Variance	-	452	-	-	-	41

Sector	Energy consumption (petajoules) Electricity	Natural gas[2]	Refined petroleum products[3]	Coal	Other fuels[4]	Greenhouse gas emissions (million metric tonnes CO_2e)
			Coal mining			
Reference data	-	-	-	-	-	-
Model data	65	34	93	79	-	26
Variance	-	-	-	-	-	-
			Crude oil production			
Reference data	-	-	-	-	-	-
Model data	107	490	163	-	-	112
Variance	-	-	-	-	-	-
			All industry			
Reference data	3,831	13,299	4,263	2,449	4,568	1,432
Model data	3,647	9,150	1,632	2,165	4,346	1,165
Variance	-184	-4,149	-2,631	-284	0	-267
			Electricity generation			
Reference data	-	5,401	1,269	20,496	-	2,381
Model data	-	5,500	1,343	20,427	-	2,048
Variance	-	100	74	-69	-	-333
			Total			
Reference data	12,381	28,267	35,737	23,053	4,569	6,493
Model data	12,191	24,167	32,636	22,591	4,347	5,839
Variance	-189	-4,101	-3,101	-462	-222	-654
Percent	-2%	-15%	-9%	-2%	-5%	-10%

Table Notes:

1. Reference energy consumption data from the Annual Energy Review 2004 (EIA, 2005). Reference greenhouse gas emissions from the US Greenhouse Gas Emission Inventory (EIA, 2006).
2. Includes propane (liquefied petroleum gas).
3. Excludes propane (liquefied petroleum gas).
4. Includes by-product gases and liquid fuels such as still gas and black liquor.

Appendix B: Other simulation results

Table 19. Effects of price increases on US sector energy demand and emissions in 2030

Economic sector	Change in electricity demand (petajoules)	Change in refined petroleum products demand (petajoules)	Change in coal demand (petajoules)	Change in natural gas demand (petajoules)	Change in GHG emissions (million metric tonnes CO_2e)
Effects of a higher electricity price					
RCI	-438	106	-	320	24
Transportation	-13	31	-	0	2
Industry	-63	5	1	68	4
Electricity generation	-	-	-	-	-
Total	-514	142	1	389	30
Effects of higher refined petroleum products prices					
RCI	71	-373	-	288	-13
Transportation	44	-811	-	9	-58
Industry	2	-196	93	78	-2
Electricity generation	0	-15	111	-92	4
Total	117	-1,395	204	284	-69
Effects of a higher coal price					
RCI	-	-	-	-	-
Transportation	-	-	-	-	-
Industry	-	86	-100	7	-1
Electricity generation	-	16	-1,610	967	-94
Total	-	102	-1,711	975	-95
Effects of a higher natural gas price					
RCI	163	280	-	-561	-7
Transportation	0	4	-	-5	0
Industry	24	125	21	-185	0
Electricity generation	0	-28	2,931	-2,367	139
Total	187	382	2,952	-3,118	133
Effects of a GHG emission price					
RCI	155	-147	-	-113	-16
Transportation	24	-455	-	3	-34
Industry	29	-28	-101	-31	-19
Electricity generation	-	31	-7,392	3,027	-550
Total	209	-600	-7,493	2,886	-619

Table notes:

1. RCI = residential, commercial and institutional
2. Energy price effects based on a 10 percent increase in energy price starting in 2010 and its effect in 2030 compared to the business-as-usual scenario.
3. Emission price effects based on a 10 dollar greenhouse gas (GHG) emission price starting in 2010 and its effect in 2030 compared to the business-as-usual scenario.

Table 20. Improvement in greenhouse gas emission intensity with and without a climate policy

	US		Canada	
	BAU	**Policy[2]**	**BAU**	**Policy[2]**
Residential, commercial and institutional	-0.7%	-2.4%	-1.0%	-1.6%
Transportation	0.0%	-0.3%	-0.2%	-0.5%
Industry[3]	-0.4%	-1.1%	0.8%	0.1%
Electricity generation	-0.4%	-2.6%	-1.5%	-2.6%

Table notes:

1. Figures are estimates of the average annual rate of change of greenhouse gas (GHG) emission intensity between 2010 and 2030 from model simulations. GHG emission intensity is emissions of greenhouse gases in each sector per unit of sector output. As defined here, it includes direct emissions from fuel combustion and industrial process emissions as well as indirect emissions from domestic electricity generation. A negative number indicates decreasing emissions per unit of sector output. For the purposes of calculating emission intensity, sector output is defined in the following units. The residential, commercial and institutional sector in square meters of floor space; transportation demand in the sum of passenger-kilometres-travelled and freight-ton-kilometres-travelled; industrial output in dollar value of shipments; electricity generation in gigajoules of electricity supplied.
2. Policy results are from a simulation of the slow-shallow carbon price scenario with trade effects.
3. Includes industrial sectors and natural gas production, crude oil production, petroleum refining and coal mining.

Table 21. Trade model simulation results with an identical climate policy in Canada and the US

Variable	Electricity		Refined petroleum products		Natural gas		Crude oil	
	BAU	Policy	BAU	Policy	BAU	Policy	BAU	Policy
P_{US}	1.00	1.27	1.00	1.03	1.00	1.10	1.00	1.03
P_{CA}	1.00	1.15	1.00	1.03	1.00	1.08	1.00	1.06
P_{ROW}	1.00	1.22	1.00	1.01	1.00	1.00	1.00	1.00
PA_{US}	1.00	1.27	1.00	1.02	1.00	1.07	1.00	1.02
PA_{CA}	1.00	1.15	1.00	1.03	1.00	1.05	1.00	1.03
$X_{US\text{-}US}$	15,465	14,964	52,751	51,236	23,624	23,491	10,341	9,656
$X_{US\text{-}CA}$	84	108	1,861	1,788	3,164	3,320	11,665	9,476
$X_{US\text{-}ROW}$	13	13	8,242	8,285	6,965	9,621	19,491	21,206
Subtotal	15,562	15,085	62,854	61,309	33,754	36,432	41,497	40,339
$X_{CA\text{-}US}$	59	46	281	266	206	165	61	57
$X_{CA\text{-}CA}$	2,132	2,187	3,728	3,498	2,248	1,903	2,239	1,833
$X_{CA\text{-}ROW}$	0	0	70	69	1,858	2,070	1,927	2,114
Subtotal	2,190	2,232	4,078	3,833	4,312	4,138	4,227	4,004
Y_{US}	1.00	1.23	1.00	1.00	1.00	1.16	1.00	0.99
Y_{CA}	1.00	1.18	1.00	0.97	1.00	1.00	1.00	0.97

Table notes:

1. All figures are model forecasts for the year 2030.
2. P_{US}, P_{CA} and P_{ROW} are supply price indexes normalised to the business-as-usual scenario for US, Canada and rest-of-the-world supply. PA_{US} and PA_{CA} are composite energy prices in the US and Canada. The six variables denoted $X_{AA\text{-}BB}$ are quantities of energy supplied by one country (BB) to another country (AA) in petajoules. Y_{US} and Y_{CA} are indexes of total expenditure in the US and Canada normalised to business-as-usual expenditure.
3. BAU results are from the business-as-usual simulation.
4. Policy results are from a slow-shallow emission price scenario simulation where the greenhouse gas price rises from zero in 2010 to 45 dollars per metric tonne CO_2e in 2030.

Appendix C: Energy flow model diagrams

Figure 21. Residential sector flow model

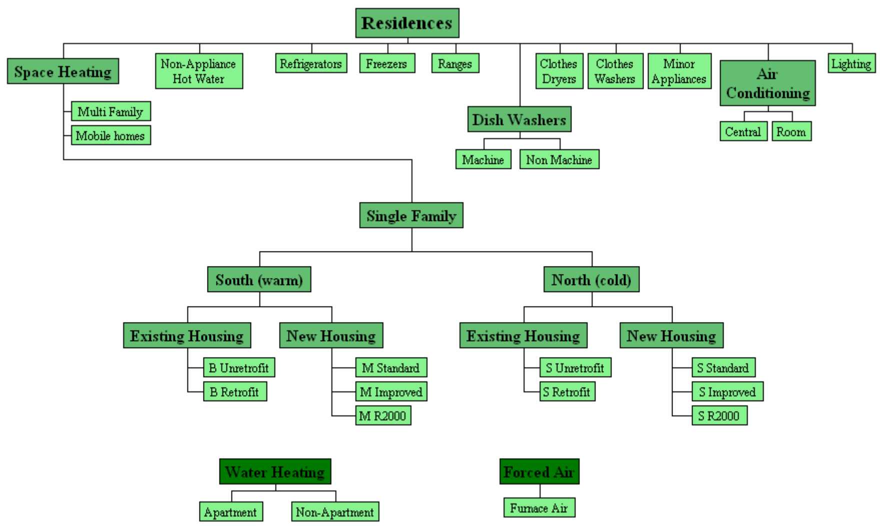


Figure 22. Commercial sector flow model

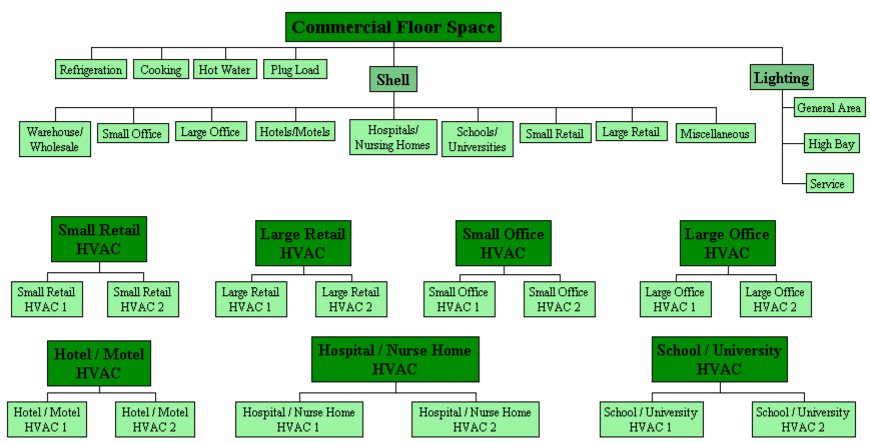


Figure 23. Transportation sector flow model

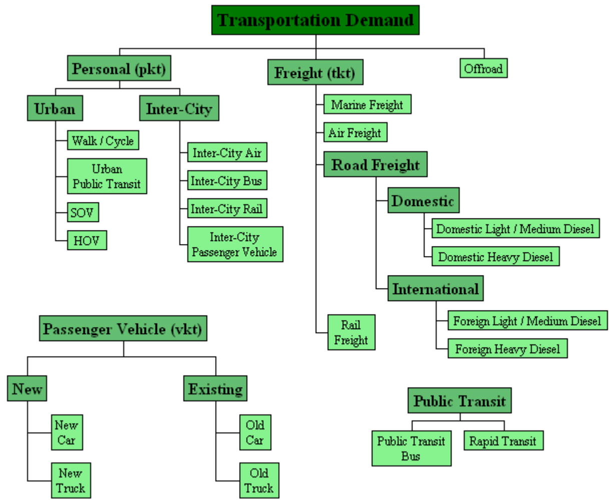


Figure 24. Chemical manufacturing sector flow model

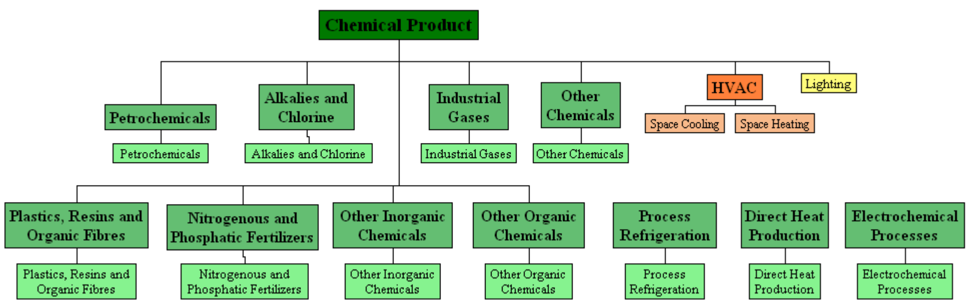


Figure 25. Industrial minerals sector flow model

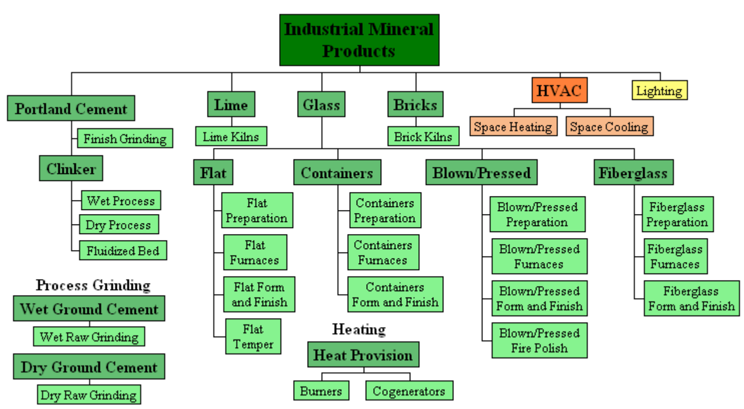


Figure 26. Steel making sector flow model

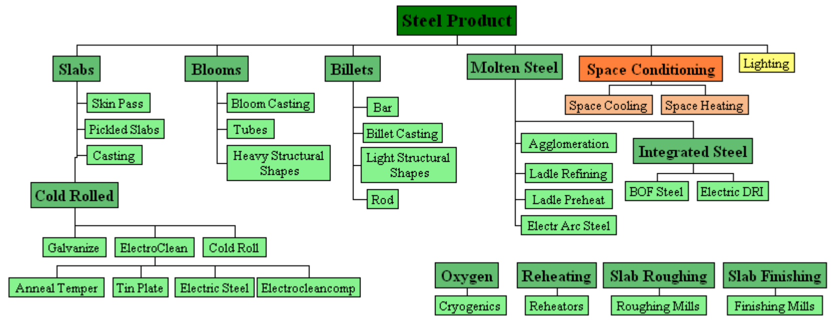


Figure 27. Metal smelting sector flow model

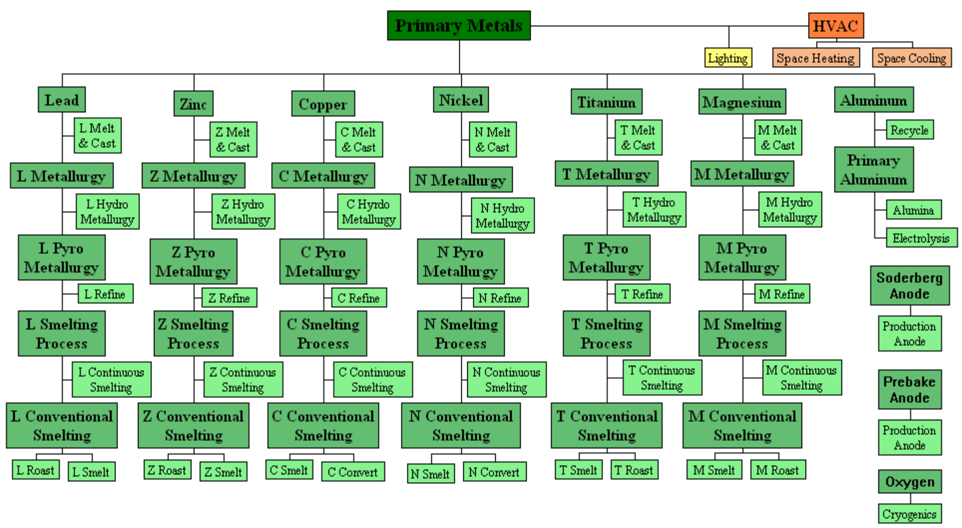


Figure 28. Mining sector flow model

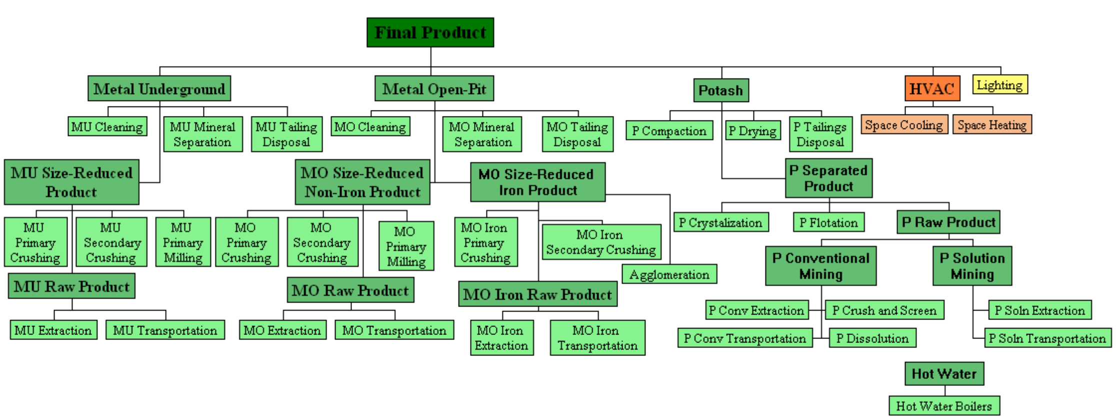


Figure 29. Other manufacturing sector flow model

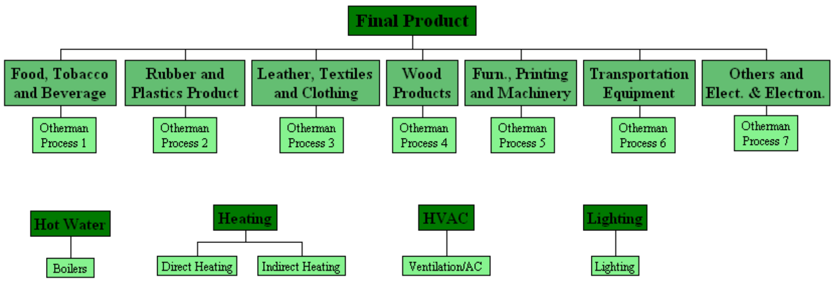


Figure 30. Pulp and paper sector flow model

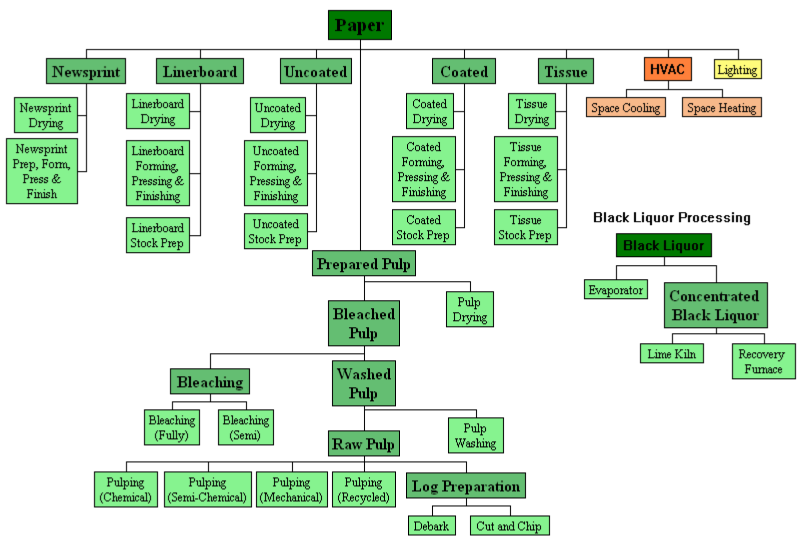


Figure 31. Crude oil production sector flow model

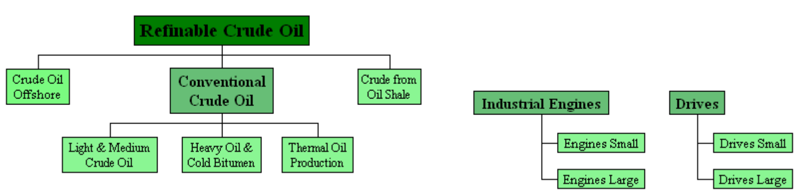


Figure 32. Coal mining sector flow model

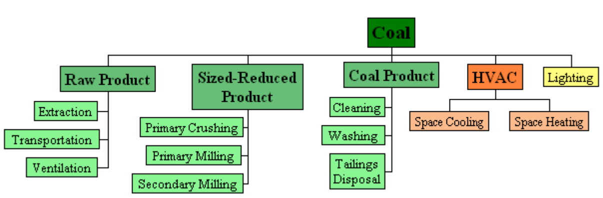


Figure 33. Petroleum refining sector flow model

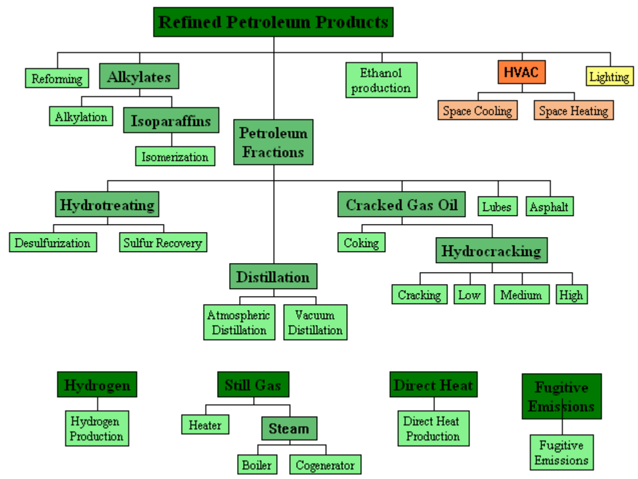


Figure 34. Natural gas production sector flow model

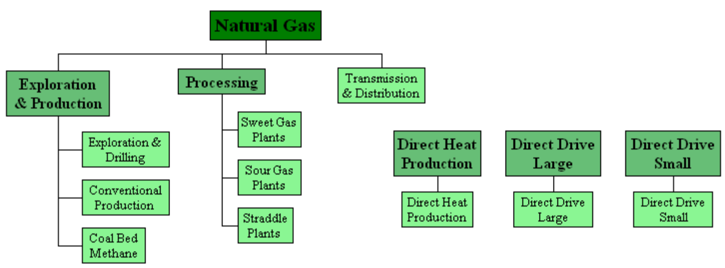


Figure 35. Electricity generation sector flow model

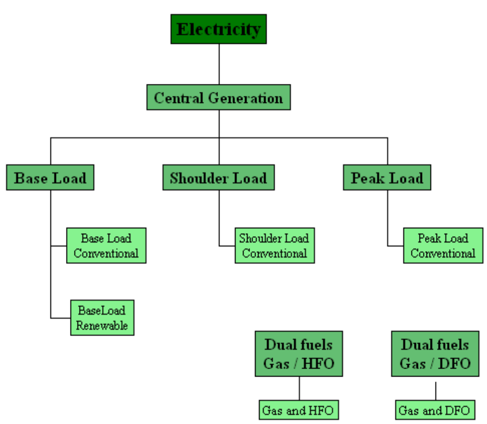
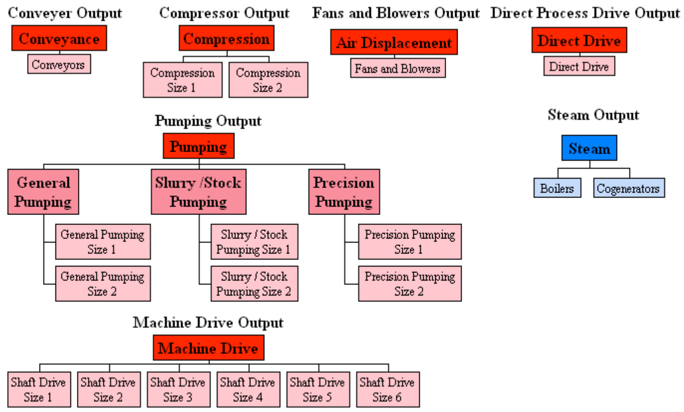


Figure 36. Auxiliary services flow model



Appendix D: Model parameters and assumptions

Table 22. Default energy trade model parameter values

	Electricity	**Refined petroleum products**	**Natural gas**	**Crude oil**
Model units	Gigajoules (GJ)	Cubic metres (m^3)	Thousand cubic metres (1000 m^3)	Cubic metres (m^3)
US				
σ	2.8	2.1	3.6	5.2
C_0 *(US$)*	19.1	350	152	79
g_f	0	0	2.5×10^{-11}	1.3×10^{-10}
k_{ICF}	1	1	1.0 to 1.3	1.2 to 2.1
k_{COP}	0.58 to 0.60	0.05	0.49 to 0.58	0.43 to 0.50
P_{ADD} *(US$)*	0	0	59 to 139	73 to 90
Canada				
σ	2.8	2.1	3.6	5.2
C_0 *(US$)*	13.9	350	226	136
g_f	0	0	7.7×10^{-11}	1.4×10^{-10}
k_{ICF}	1	1	1.0 to 1.3	1.2 to 2.1
k_{COP}	0.8 to 1.2	0.03 to 0.04	0.47 to 0.56	0.45 to 0.65
P_{ADD} *(US$)*	0	0	26 to 122	96 to 134
ROW				
E_s	0.3	0.6	-	-
C_0 *(US$)*	-	-	175	26
g_f	-	-	4.0×10^{-12}	2.5×10^{-11}
k_{ICF}	-	-	1.0	1.0
k_{COP}	-	-	-	-
P_{ADD} *(US$)*	-	-	240 to 349	215 to 257

Table 23. Global warming potential of greenhouse gases

Gas	Global warming potential (CO_2 equivalent)
Carbon dioxide CO_2	1
Methane CH_4	21
Nitrogen oxide N_20	320

Table 24. Discount rates for investment decision-making.

Sector	Technologies	Discount rate
Residential	Space heating	0.3 to 0.4
	Building shell	
	Refrigeration	
	Other appliances	
Commercial	Heating, ventilation and cooling	0.3 to 0.4
	Refrigeration	
	Cogeneration	
	Other	
Industrial	Process technologies	0.35
	Auxiliary technologies	0.5
Electricity generation	Generation technologies	0.2
Transportation	Private vehicles	0.08
	Public transit	0.08
	Road freight	0.35
	Rail	0.125
	Marine	0.125
	Air	0.125

Appendix E: Recommended model improvements

Trade model and energy supply models:

- Review literature on crude oil and natural gas supply and investigate whether the trade model used here could be improved.
- Extend trade model to other traded goods – especially energy intense goods such as industrial minerals, steel, pulp and paper, chemicals and other metals.
- Consider lower Armington elasticities for short-run trade adjustments.
- Include crude oil demand by the rest of the world.
- Improve supply price model for natural gas and refined petroleum products imports from the rest of the world.
- Use a 2-level Armington model.
- Include endogenous coal supply and demand.

Sector flow models:

- Add technology choice to air, rail and marine transportation and the possibility of mode shifting in long distance personal transportation and freight transportation.
- Review forecasted electricity use in residential, commercial and other manufacturing and revise models accordingly.
- Examine the sensitivity of results to US electricity generation technology coefficients – especially the costs of CCS and IGCC, technology learning rates, and assumptions about nuclear power.
- Update the residential and commercial sector models with US data on building shells and heating, ventilation and cooling (HVAC) technologies.
- Review estimates of renewable electricity generation potential in the US and adjust model accordingly.

- Consider using a cost-curve method to simulate technologies with limited capacity and increasing marginal costs – e.g. wind, biomass and carbon sequestration.
- Improve the modelling of non-renewable resource extraction – consider methods to simulate technology choice based on increasing marginal costs of production in the sector models.
- Calibrate year 2000 emissions in electricity generation, commercial, chemical manufacturing and petroleum refining to reference data.
- Calibrate sector models to latest historic data – e.g. 2005.
- Review rate of improvement in emission intensity in petroleum refining, other manufacturing, and pulp and paper (compare with EIA reference scenario).
- Add gas-to-liquids and coal-to-liquids technology for production of transportation fuels.
- Add additional CCS capability to industrial models – e.g. biomass combustion, cogeneration, petroleum refining and chemical manufacturing.
- Get cost and potential reserve data for non-conventional oil and gas production – e.g. coal bed methane, shale gas, oil shale, and synthetic natural gas (SNG) from liquids and coal.
- Improve estimates of technology costs in chemical manufacturing sector.
- Model more of the electricity use in natural gas extraction and crude oil production models with standard auxiliary technologies – electric motors, pumps and compressors.
- Include technological improvements in electricity transmission efficiency.

Other general improvements:

- Update economic forecasts and energy prices to latest forecasts.
- Run simulations for alternative scenarios – e.g. a high oil price.
- Improve the computational speed of the model.

- Carry out a comprehensive sensitivity analysis to identify important parameters.
- Consider parametric uncertainty and estimate the uncertainty of model results.
- Account for revenue redistribution due to an emission price.
- Add demand feedbacks to final consumption sectors to simulate macro-economic adjustments.
- Extend the simulation period to 2050.
- Link ethanol supply model to ethanol demand.
- Consider benefits of adding hydrogen production to supply models.

Possible future research goals:

- Simulate a wide range of climate policies and policy packages such as a renewable electricity standard, a vehicle emissions standard and a carbon sequestration standard.
- Consider the effects of import tariffs and energy security policy in the US.
- Consider the option of operating this model in combination with a CGE model to account for macroeconomic adjustments.
- Link models of other global regions by simulating global trade and investment.

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