DESIGN AND APPLICATION OF A TECHNOLOGICALLY EXPLICIT HYBRID ENERGY-ECONOMY POLICY MODEL WITH MICRO AND MACRO ECONOMIC DYNAMICS

by

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Abstract

Are further energy efficiency gains, or more recently greenhouse gas reductions, expensive or cheap? Analysts provide conflicting advice to policy makers based on divergent modelling perspectives, a 'top-down / bottom-up debate' in which economists use equation based models that equilibrate markets by maximizing consumer welfare, and technologists use technology simulation models that minimize the financial cost of providing energy services. This thesis summarizes a long term research project to find a middle ground between these two positions that is more useful to policy makers.

Starting with the individual components of a behaviourally realistic and technologically explicit simulation model (ISTUM - Inter Sectoral Technology Use Model), or "hybrid", the individual sectors of the economy are linked using a framework of micro and macro economic feedbacks. These feedbacks are taken from the economic theory that informs the computable general equilibrium (CGE) family of models. Speaking in the languages of both economists and engineers, the resulting "physical" equilibrium model of Canada (CIMS - Canadian Integrated Modeling System), equilibrates energy and end-product markets, including imports and exports, for seven regions and 15 economic sectors, including primary industry, manufacturing, transportation, commerce, residences, governmental infrastructure and the energy supply sectors.

Several different policy experiments demonstrate the value-added of the model and how its results compare to top-down and bottom-up practice. In general, the results show that technical adjustments make up about half the response to simulated energy policy, and macroeconomic demand adjustments the other half. Induced technical adjustments predominate with minor policies, while the importance of macroeconomic demand adjustment increases with the strength of the policy. Results are also shown for an experiment to derive estimates of future elasticity of substitution (ESUB) and autonomous energy efficiency indices (AEEI) from the model, parameters that could be used in long-run computable general equilibrium (CGE) analysis.

The thesis concludes with a summary of the strengths and weakness of the new model as a policy tool, a work plan for its further improvement, and a discussion of the general potential for technologically explicit general equilibrium modelling.

Dedication

To my mother - Florence Thompson to the world, "Flo" to her friends, and "Mom" to my brother and I. Long may you travel the byways of Heaven.

"If you can't fly, climb."

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- Dr. Mark Jaccard, my senior supervisor, for his faith in my ability.
- My grandmother "Babe" Thompson, whose strength, stories and basic good sense carry me through.
- Ren, my love, my wife, my partner in crime.

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List of Abbreviations and Acronyms

AEEI	Autonomous Energy Efficiency Index
AIM	Asia Pacific Integrated Model
APL	Advanced Programming Language
BAU	Business-as-Usual
CAC	Criteria Air Contaminants
CASGEM	Canadian Sectoral General Equilibrium Model
CEOU	Canada's Energy Outlook – An Update
CES	Constant Elasticity of Substitution (Production Function)
CGE	Computable General Equilibrium
CIMS	Canadian Integrated Modeling System
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CRTS	Constant Returns to Scale
DDF	Demand Decoupling Factor (MACRO-MARKAL)
EIA	Energy Information Administration
ECT	Energy Conservation Technology (MACRO-MARKAL)
ERC	Expected Resource Cost
ESUB	Elasticity of Substitution
GHG	Greenhouse Gas
GTEM	Global Trade and Environment Model
IPCC	International Governmental Panel on Climate Change
MAM	Macroeconomic Model (NEMS)
MARKAL	Market Allocation Model
MIT-EPPA	Massachusetts Institute of Technology – Emissions Prediction and Policy Analysis Model
MS-MRT	Multi-Sector Multi-Region Trade Model
NEMS	National Energy Modelling System
NRCan	Natural Resources Canada
OEE	Office of Energy Efficiency
PPC	Perceived Private Cost
SGM	Second Generation Model
TEC	Techno-Economic Cost
UNFCCC	United Nations Framework Convention on Climate Change
USDOE	United States Department of Energy

1 Introduction & Research Objectives

1.1 The current and future requirements of energy and climate policy modelling

> "Between human beings there is a type of intercourse which proceeds not from knowledge, or even from lack of knowledge, but from failure to know what isn't known".
>
> J.K. Galbraith, "The Great Crash 1929" pp. 97-98

In recent decades, the general public and policy makers have become aware that economic activities have an intrinsic impact on the viability of the environment. All economic byproducts, including seemingly innocuous ones such as carbon dioxide (CO_2), can be dangerous given a high enough concentration. This growing understanding of the interaction between the environment and economic activity is leading to a demand for greater regulation of all the economy's waste products.

Not all wastes are equal, however; the deleterious effects of waste products vary enormously, from the extremely damaging nature of polychlorinated biphenyls (PCBs) and chlorofluorocarbons (CFCs) to the locally benign nature of CO_2 emissions from fossil fuel combustion.[1] CO_2 is potentially dangerous in terms of how fast its concentration changes in the atmosphere; it is believed to be the most important greenhouse gas (GHG), and thus a possible cause of climate change. It would be ruinously expensive to simply ban the emission of GHGs as

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[1] PCB's are strong carcinogens, while CFC depletes the stratospheric ozone layer, without which ultraviolet radiation from the sun would destroy most exposed life.

one might the use of CFCs or PCBs; this implies that there is a balance to be struck between the emission of moderately harmful wastes and their value to human welfare.

According to economic theory the optimal balance between the benefits and damages caused by economic activity occur at the point where their incremental, or *marginal*, effects are equal (Field and Olewiler 1995). The theory is clear, but the application is fraught with difficulty; while the marginal benefits of an activity producing emissions are typically well known, the marginal damages are usually difficult to ascertain. For this reason environmental regulations are normally established as *bans* for highly dangerous substances such as PCBs, and *flow* or *concentration* targets for the moderately dangerous such as GHGs. A commonly discussed goal is to stabilize global CO_2 at 550 parts per million (IPCC 1990, 1992, Weyant *et al.* 1999). This concentration target is to be achieved by a sequence of flow targets, beginning with the worldwide goal, established as the Kyoto Protocol to the United Nations Framework Convention on Climate Change, to reduce the collective GHG emissions of signatories to the protocol to 5% less than 1990 levels by 2010 (UNFCCC 1992, 1997).

Once a quantitative target is established, the challenge is to meet it at the least cost; this requires actions, and policies to implement those actions. The efficacy and cost of these policies is an empirical question that requires the ability to model the complex adjustments of the economy to a given policy proposal. This has led to a demand for quantitative models of the economy that explicitly represent the change in emissions in response to a given policy proposal, as well as the associated financial and welfare costs.

The requirements of models used for analyzing environmental policy are different from those used for fiscal or social policy. The amount of waste emitted for a given level of economic activity is a function of both the amount of industrial, commercial, residential and transportation activity, and the particular stock of buildings, processes, and equipment in use in each of these sectors. Models of the economy used to assess the cost of meeting our environmental policy goals, especially in relation to our GHG emission commitments, must include the above sectors at a level of technological detail and feedback sophistication that captures each sector's ability to adjust to potential policies. How do currently existing modelling systems measure up to these demands?

A standard method for evaluating modelling systems is to categorize them in a conceptual framework that allows the identification of strengths and weaknesses in their analytical capabilities. In the next section, I look at a framework for policy analysis in the energy sphere based on the "top-down" and "bottom-up" approaches to modelling the energy-economy system. I then propose an alternative to this framework in order to focus on an additional dimension, a dimension that illuminates a gap in our analytical capability.

1.2 The top down / bottom up conundrum

Economic models used for analyzing energy policies are commonly classified as being either "top-down" or "bottom-up" (Edmonds *et al.* 2000, Jacoby 1998, Löschel 2002, Wene 1996). These classifications emphasize the difference between how the models describe the function of the economy in terms of technological detail and micro and macro economic dynamics. Top-down models generally view the economy in large aggregates of capital, labour, materials, and energy; these are also called “factors of production” and are measured in monetary terms. These inputs are brought together to form outputs using production functions, which describe the possibility for input substitution through elasticities and long term changes in input productivity through adjustment parameters. Most top-down models do not describe technologies or processes, although they may be integrated with energy supply models that include an explicit treatment of some technologies. Bottom-up models, on the other hand, operate at the level of technologies and processes used to provide energy services. They describe, with varying degrees of complexity, the capital stock that provides our energy services now and in the future, and are generally more likely to interpret economic inputs and outputs in physical instead of monetary terms (e.g. energy is counted in gigajoules instead of dollars).

In terms of policy analysis, because top-down models start with parameters estimated or guessed from historic data, wherein consumers and firms are assumed to be efficient in their input and consumption choices, any policy adjustment is likely to cost something relative to the business-as-usual (BAU) case. In this world view unutilized “no-regrets” efficiencies are illusory and a misleading guide to policy makers. The private market is assumed to be the most efficient vehicle for the allocation of inputs and selection of outputs, given everything is priced properly (Sutherland 2000).[2] This worldview is mute on what outputs should be produced; consumers' choices are "sovereign".

Bottom-up modellers, on the other hand, see the economy through the eyes of an engineer. They start with a set of available technologies and tell us which ones we should have been using if we wished to minimize expected financial cost (generally not including risk), and which ones we should use in the future. Hence, they generally find negligible or even negative costs to further energy efficiency and limitation of greenhouse gases. The bottom-up technologists generally argue that the economy is not efficient in its uptake of new technologies, and that there are many technological ways to improve efficiency, reduce emissions and possibly increase welfare. Efficiency is not just a question of proper pricing. Active government interference in the form of policy (government funded research and development, standards, subsidies, information campaigns) is necessary to bring new technologies to market and to exclude welfare reducing technologies, all to promote a genuine social good not provided by the market.[3] In sum, the two modelling paradigms lead not just to differing methods and results but also to differing policy recommendations. This ongoing fundamental disagreement has profound ramifications for energy policy.

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[2] Most economists would allow that most waste products of the economy are improperly priced in terms of their negative effect on consumer welfare.

[3] There is an ongoing debate and literature concerning whether the market is replete with "failures" that prevent new technologies from emerging. The common counter argument is that consumers are sensibly risk averse and that they will not adopt a "risky" new technology unless there is strong and compelling reason to do so. In this case the supposed "market failures" are not failures, but rational behaviour in the face of risk.

1.2.1 Top-down models, their limitations and attempts to alleviate them[4]

Top-down models characterize consumers' consumption choices and the technical relationships between a firm's inputs to production using equations; these parametric relationships determine how the consumption of goods and services, and the share of inputs used in producing them, will change in response to a change in relative input prices. These models may take a full or partial equilibrium approach; in the former case, they balance supply and demand in every market, and in the latter they deal with only a subset of markets. They may operate at differing scales, be it global, national, or regional, depending on the context. They may be classified as open-ended, growth driven "macro-econometric" or close-ended "general equilibrium". In the former, the dynamics of the model are driven by equations based on long-run time series data, with no assumption of equilibrium. In the latter, the dynamics are driven by factor price equilibrium between producers and consumers of inputs and outputs, with consumer utility or firm profit maximization as the driver (Löschel 2002). In both these modelling types, because there is no direct modelling of technological change, the rate at which the energy efficiency of the capital stock evolves is usually determined by long-run substitution elasticities between capital and other inputs (ESUBs) and an autonomous energy efficiency index, or AEEI. The AEEI parameter indicates how the amount of energy required to produce a given level of output changes over time because of technological change, independent of

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[4] Some examples of top-down models used in Canada for climate change analysis include: CASGEM (Iowerth *et al.* 2000), G-Cubed (used for international effects for CASGEM) (McKibbin and Wilcoxen 1999), R. McKitrick's computable general equilibrium (CGE) modelling work (McKitrick 1997, 1998, 1996) and TIM/RIM (Informetrica 1998).

energy price. Both these critical parameters may be estimated or guesstimated. Estimation has the benefits of observed behaviour as a guide, but this observed behaviour may be invalid in a future world with differing technologies and priorities. Guesstimation seems to be the usual case, with the benefit that the modeler can adjust the parameter to fit plausible future situations.

The AEEI and ESUB parameters, and how they are set, highlight a key limitation for using top-down models for energy policy - their limited depiction of the capital stock and technological development. They can miss important dynamics associated with the natural rate of stock turnover (capital vintaging), alternative available technologies, the potential for retrofitting existing technologies, and the effects of cumulative production and market penetration on both the real and perceived cost of a technology (Grübler *et al.* 1999a, 1999b, Jaccard *et al.* 2003b, Löschel 2002). These limitations make it difficult to model both technology specific policies, such as subsidies, emissions standards, and technology portfolio standards, and more general polices that are contingent on specific technology characteristics, such as an emissions charge. A windmill, natural gas turbine and coal boiler may all produce electricity, but the cost, fuel and emissions profiles will all be different. In sum, top-down models lack *technological explicitness.*

The technical weakness of the top-down modelling approach has not gone unrecognized. While the use of AEEI and ESUBs is the most common method for endogenizing technical change in top-down models, many other methods have been attempted. Econometricians have tried to address the issue by developing dynamic models (Watkins 1992). These models incorporate separate dynamic variables to interpret capital stock evolution in the past and thereby predict its evolution in the future. Because this approach is non-specific about the vectors of technical change, it has difficulties accommodating key and possibly revolutionary advancements that we know may enter the capital stock in the near future. We also do not know what new technologies, and old technologies in new uses, will emerge in a greenhouse gas limited world because there has never been motivation for people to spend time and resources on developing them. Other econometricians have attempted to link technical change to more specific vectors like research and development, learning by doing (cumulative production) and, finally, to find the hidden "prices" that drive "non-price induced" energy induced efficiency (Jaffe *et al.* 2002, Löschel 2002). Another common approach to addressing the technical weakness of top-down models has been to pair them with technically explicit linear programming models of the energy supply system (Berger *et al.* 1987, Hoffman and Jorgenson 1978, Manne and Wene 1992, Wene 1996). A more recent approach is the use of disaggregated production functions and parameters specific to different sectors of the economy. Two examples are the Second Generation Model (SGM) (Edmonds *et al.* 1991, Sands 2002, Sands and Schumacher 2003), and the Massachusetts Institute of Technology Emission Prediction and Policy Analysis Model (MIT-EPPA) (Babiker *et al.* 2001). In the main, however, most top-down models depict most of the evolution of energy demand in an aggregate fashion using elasticities and efficiency indices. This makes the choice of ESUB and AEEI parameters critical to the plausibility of the results of these models.

1.2.2 Bottom-up models, their limitations and attempts to alleviate them[5]

The inability of top-down models to track characteristics of the capital stock important to energy policy, specifically fuel use and emissions per unit produced, led to the development of both demand and supply side "bottom-up" models. Bottom-up models explicitly account for technologies and engineering processes instead of using abstract mathematical production functions to bring inputs together to make outputs. The penetration of new technologies and processes is usually modelled based on the relative financial cost and performance characteristics of these technologies. Most bottom-up models choose technologies by minimizing the financial cost of providing an exogenously derived demand for energy services, given a set of factor prices. More complex bottom-up models, including MARKAL (Fishbone and Abilock 1981, Loulou and Lavigne 1996) and ISTUM (Jaccard and Roop 1990, Nyboer 1997), keep track of individual technology stocks, thereby incorporating the over-time effects of capital turnover.

Bottom-up modelling is sensitive to the quality of technology data and the method used for firm and household purchasing behaviour. The data question is individual to the model operator but the behaviour question is not - do consumers

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[5] Some examples of bottom-up models used, or proposed to be used, in Canada: Canadian Mark*et al.*location Model (MARKAL) (Berger *et al.* 1992), Intra Sectoral Technology Use Model (ISTUM) (Jaccard and Roop 1990) (Nyboer 1997) and Energy 2020 (SSI 1996).

and managers really make their technology purchasing decisions purely by minimizing financial costs? Anyone who has purchased a car knows that financial cost is only one factor in the decision; in most shopping comparisons there will be a selection of eligible goods that perform what seems to be the same function, but have characteristics other than cost that affect their utility (e.g., red and grey cars cost the same). In addition, different consumers and managers will weight different attributes differently – some are more risk averse, some less, some like new things, some prefer the tried and true. Most bottom-up models lack the *behavioural realism* inherent at an aggregate level in top-down models. Bottom-up models are also partial equilibrium models, in that they generally model only the technical choices associated with providing an exogenously specified good or service for a single market. They usually take no account of how fuel prices may change in response to new technology choices or how demand may change for a good or service with a change in price, saying nothing of the wider effects on income, employment, government revenue etc. In sum, they lack *equilibrium feedbacks.*

A prominent set of methods to add equilibrium feedbacks to a bottom-up model are those made by the operators of the MARKAL family of linear optimization models. Basic MARKAL (Fishbone and Abilock 1981) integrates energy demand and supply, allowing energy service demand to drive energy processing, production and pricing. MARKAL- MACRO (Manne and Wene 1992) uses a simple growth model composed of a consumer utility curve and a basic production function to cover the parts of the economy not explicitly modelled in

MARKAL. MARKAL-ED (Loulou and Lavigne 1996) added price elastic demands for products. MARKAL-MICRO (ETSAP 1999) uses a mixture of elastic demands and inter-sector substitution equations, mainly for transportation, driven by consumer utility maximization. 15 region MARKAL (Labriet *et al.* 2004) takes the logic of MARKAL to perhaps its logical conclusion by combining 15 different MARKAL models from around the world, including elastic demands, into a coordinated system. However, as a linear optimization model MARKAL is not behaviourally realistic by design. In seeking out the lowest financial cost method of reaching a policy target, it ignores how firms and consumers will actually behave given different perceptions of risk and intangible preferences in their decision-making.

A bottom-up model that has made significant strides toward modelling firm and consumer behaviour more realistically is the Intra-Sectoral Technology Use Model (ISTUM) (Jaccard and Roop 1990, Nyboer 1997). ISTUM attempts to simulate real equipment purchasing behaviour by using a cost-minimization algorithm that combines the financial and the intangible. The algorithm employs observed purchasing discount rates, firm heterogeneity and adjustments to include known intangible costs, risk and lost option value[6], as well as the more usual financial capital, labour, fuel and emission costs. ISTUM, however, lacks significant equilibrium feedbacks - it cannot simulate how the effects of a

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[6] Please note the term "option-value", the value of additional information pertaining to a decision gained by delaying it, is purposefully used in favour of the similar "quasi-option value". Please see Appendix A for a discussion of the choice of these two terms.

proposed energy policy might affect the interaction of energy supply and demand, or the overall demand for goods or services.

It may be convincingly argued that full equilibrium top-down models are necessary to capture the complex effects energy and climate change policy may have on the economy. It is not as convincing that the way they include technological change is sufficiently accurate to describe the potential changes in the technology stock. Bottom-up models, which *can* capture these changes, cannot currently replace top-down models for simulating the economy wide effects of climate change policy.

1.2.3 The hybrid

The weaknesses and strengths of the two approaches suggests the question of how the best of each could be brought together in a single modelling framework, or "hybrid" (Böhringer 1998, Jaccard *et al.* 1996). There have been several attempts by operators of both top-down and bottom-up models to include elements of the other approach. One of the most ambitious efforts has been the National Energy Modelling System (NEMS) model of the Energy Information Administration of the US Department of Energy (USDOE/EIA 1998-2003). NEMS is the primary energy policy analysis tool of the US Department of Energy. NEMS divides the economy into four demand sectors (residential, commercial, industrial and transportation), three energy-processing sectors (electricity, petroleum refining and natural gas transmission and distribution), and four primary energy supply sectors (coal mines, natural gas, oil supply and renewables). To these are added macroeconomic and international energy trade modules. However, due to the circumstances under which it was built, the individual modules are of varying degrees of quality and depth, and most have differing operating frameworks (linear programming for electricity, logistic for transportation, experience curves for industry and macro-econometric for the macroeconomy). This has made the model cumbersome to use, and ill suited for use by smaller, less well funded research groups for purpose of answering specific research questions.

1.2.4 An alternative paradigm: The three dimensions framework

The following three characteristics suggest a different classification system for energy-economy models:

- **Technological explicitness** is necessary because emissions and fuel consumption are a direct result of the technology stock in use, not just necessarily the service desired.
- **Behavioural realism** is required to gauge the response of firms and households to a policy, especially if it is implemented using economic as opposed to regulatory instruments.
- **Equilibrium completeness**. Energy and emissions policies will generate feedbacks throughout the economic and environmental system.

Figure 1 provides a graphic of this new classification system. The vertical dimension shows the degree to which a given model is technologically explicit. The dimension moving into the cube, "equilibrium completeness", shows the degree to which a given model incorporates all the feedback effects that may be triggered by a policy, including price effects, demand effects and possibly even feedbacks by the environment. Finally, the dimension moving from left to right is the degree to which a model accurately incorporates human behaviour in the face of a policy. The further a model moves out on all three dimensions, the ideal model being in the top right back corner, the more encompassing its analysis. The standard top-down model, at the bottom on the right near the back of the cube, is high on equilibrium completeness and behavioural realism, but low on technological explicitness. The standard bottom-up model, at the top on the left near the front of the cube, is high on technological explicitness but low on behavioural realism and equilibrium completeness.

Figure 1 Graphic depiction of the three dimensions framework

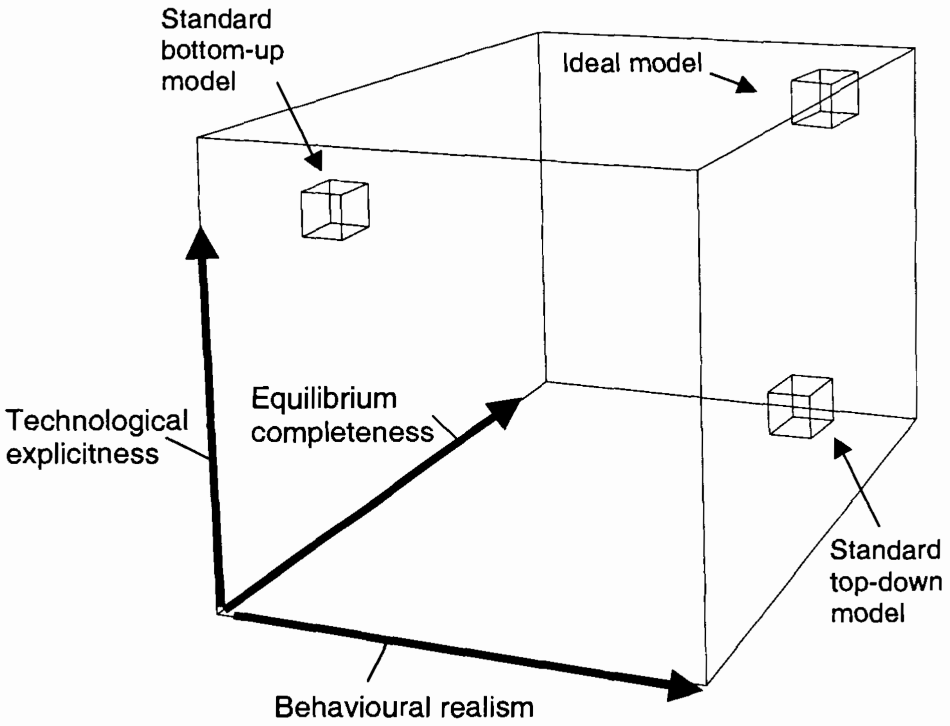
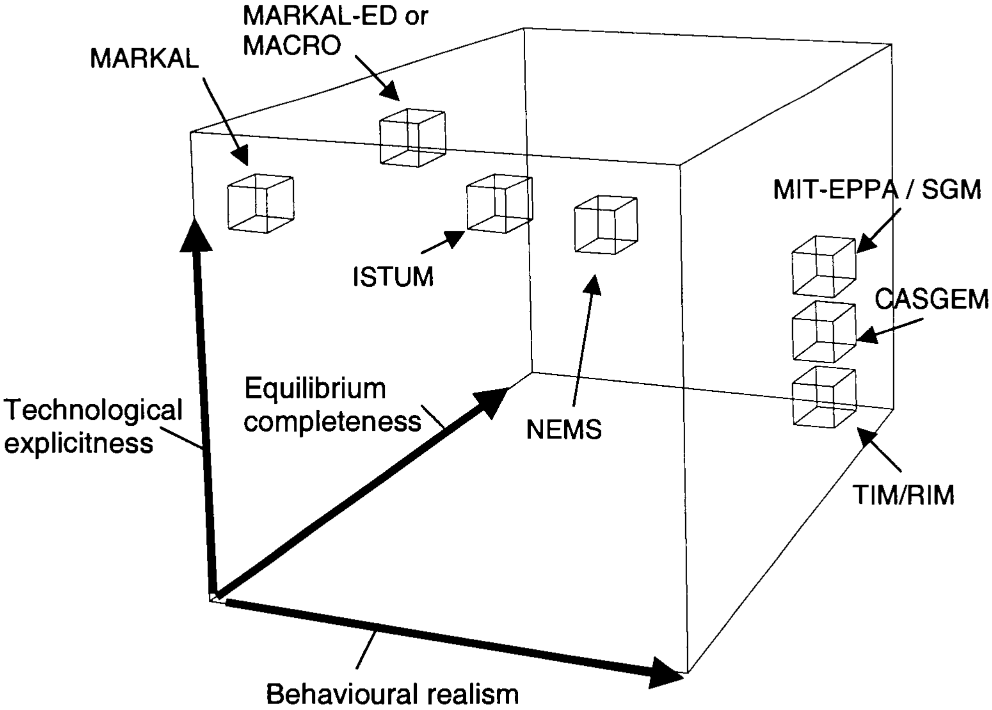


Figure 2 places some representative models in this new context.

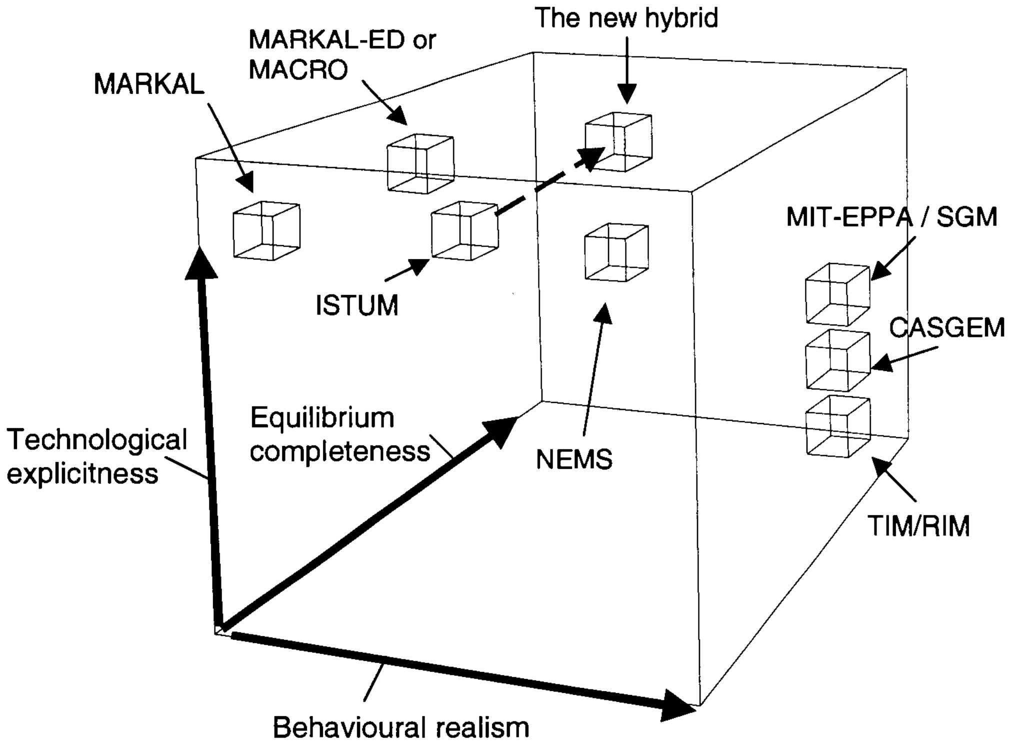
Figure 2 Some common models within the three dimensions framework



The most technologically descriptive model with the least feedbacks and behavioural realism, MARKAL, is in the top front left of Figure 2, while the macroeconomic model with the least technological detail, TIM/RIM, is in the bottom back right. ISTUM is further to the right than MARKAL because its technology choice algorithms are behaviourally realistic, while NEMS is further to the back because it incorporates equilibrium feedbacks. ISTUM and NEMS are about the same with respect to behavioural realism, although NEMS looks further to the right because it is nearer the back of the cube. Among the top-down models CASGEM is higher than TIM/RIM because of its sectoral disaggregation, while MIT-EPPA and SGM, which use sophisticated mixes of production functions to depict technology in sectors, are higher still.

The three-dimension framework can be used to articulate criteria for an improved hybrid. The hybrid model would be *technologically explicit* - it would have a consistent and explicit treatment of the fuel, labour, cost and lifetime profile of both existing and nascent technologies, including the potential for retrofitting and cost changes related to economies of scale and learning. It would be *behaviourally realistic* - it would have a consistent set of requirements and methods for setting the parameters that inform consumer and firm preferences, including costs, risk, option value and other intangibles. Finally, the hybrid would include all relevant *equilibrium feedbacks.* Depending on the jurisdictional context, these may include domestic and foreign supply and demand balancing for energy, goods and services, the balancing of consumption, savings and leisure by consumers and finally, capital flow, taxation and interest rate effects engendered by all the above. Figure 3 shows how the new hybrid would fit in the framework were it constructed from the ISTUM technology simulation model.

Figure 3 The three dimensions model with the proposed hybrid



1.3 Research objectives

My research objectives are as follows:

- Review the detailed methods used to model production and technology evolution in models used for climate policy analysis. Target any insufficiencies and use them to formulate research questions.
- Explore methods for building a more coherent and usable hybrid to answer these research questions. Design and construct the hybrid model.
- With the objective of improving energy policy modelling, and hence information to policy makers, answer the research questions by using the hybrid model by itself and by assessing explicit or implicit parameter values of other energy economy models used for GHG abatement policy analysis.

1.4 An outline of the thesis

The general outline of this thesis loosely follows the “introduction, literature review, methods, data, results, discussion and conclusions” model used for standard research papers, but given its varied nature, components of each will be found in different chapters. For example, Chapter 2, “Literature Review and Research Questions”, contains the literature review detailing the theoretical issues behind the policy modelling issues, but Chapter 3, “Methods and Data“, contains the literature review used to establish criteria and methods for building a hybrid model. As such, my use of the standard research paper layout is in spirit, if not exact detail.

Chapter 1 provides the general rationale and objectives of my research program. Chapter 2 details the historic AEEI and ESUB debates, along with the findings of a survey of current practice in energy and climate change policy modelling. It finishes with detailed research questions that emerge from AEEI and ESUB literature and the survey of general practice. Chapter 3 provides the methods and data used for the different components of the thesis. It details the theory and methods used to build a hybrid model for answering the research questions, the estimation techniques used for calculating the AEEI and ESUB parameters from the hybrid model, and finally, the methods used for policy analysis that has been conducted with the model. Chapter 4, the results section, provides the AEEI and ESUB parameter estimates from the hybrid and a demonstration of its policy analysis potential. Chapter 5 provides a critical assessment of how well the hybrid met its construction criteria, and a discussion of the results. Chapter 6 provides a summary of the key findings of the thesis and a roadmap for research that may be derived from it. Several appendices detail topical issues, survey findings, mathematical methods, data sources and parameter estimates.

2 Literature Review & Research Questions

While bottom-up models provide the necessary technical detail for energy policy analysis, only top-down models currently provide an adequate level of behavioural realism and economic feedbacks to conduct energy policy analysis. Their handling of production, however, tends to be abstract and far from uniform, while technical change is usually ignored, over-simple or misspecified. Improvement of all these elements is a key objective of this research project. This chapter begins with an examination of the historic debates surrounding the AEEI and ESUB parameters used in top-down models, and then moves to a survey of models currently used for energy and climate change analysis, with a focus on how they depict production and the evolution of technology. It finishes with a summary of the insufficiencies in current top-down methods, specifically those related to the AEEI and ESUBs, and a series of research questions to be addressed.

2.1 The historic AEEI and ESUB debates

The first vigorous debates over the AEEI and ESUB parameters began in the mid-1970's, and were triggered by the large and lasting increases in the relative price of oil that followed the Arab oil embargo of October 1973 - March 1974. Before this time, energy use and economic activity had grown and shrunk in even proportion, implying that they are used in a static ratio to one another. This was certainly true in the short-run, as energy use is tied to the existing capital stock, but was it true in the long-run, the period over which the capital stock is retired and re-purchased? In terms of energy policy analysis two fundamental questions were being asked. First, given a higher relative price of energy, how easily can technologies with a higher energy efficiency, either currently existing or not, replace the low efficiency stock (ESUB)? Second, how fast do new higher efficiency technologies develop, independent of price effects (AEEI)? This led to two separate but interconnected debates.

2.1.1 The debate over the elasticity of substitution between capital and energy

The key energy-modelling question of the early 1970's was whether capital and energy were long-run complements, which would entail high long-term adjustment costs to the rise in the price of oil, or substitutes, with appropriately lower costs.[7] During this period, several studies calculated capital (K) for energy (E) substitution elasticities.[8] Some found a complementary relationship (Berndt

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[7] If the use of an input falls as the price of another rises, they are complements. If the use of an input rises as the price of another rises, they are substitutes.

[8] The elasticities of substitution (ESUBs) discussed here are Allen partial elasticities of substitution. This form of elasticity tells us how the ratio of input usage (defined as shares of the cost of production) changes in response to the ratio of prices. The elasticity of substitution between two inputs (Q_i and Q_j) with prices P_i and P_j is given by Equation 1;

$$\sigma_{ij} = \frac{\partial Q_i / Q_j}{\partial P_j / P_i} \bullet \frac{P_j / P_i}{Q_i / Q_j} \qquad (1)$$

This definition is usually attributed to R. Allen, who developed it in an alternate form in *Mathematical Analysis for Economists* (New York: St.Martin's Press, 1938), pp.504-509 (Nicholson 1992). There is a vigorous debate about the appropriateness of the Allen partial formulation vs. that for the Morishima and other methods for calculating elasticities of substitution. The Allen partial is used because it is the most commonly used in the literature, and therefore the most comparable.

and Jorgenson 1973, Berndt and Wood 1975, Fuss 1977, Hudson and Jorgenson 1974, Magnus 1979). Others found the K for E relationship to be one of substitutability (Griffin and Gregory 1976, Halvorsen and Ford 1979, Pindyck 1979). The key difference between the former and latter studies is that while the former used inter-temporal data for individual nations, the latter utilized international cross section data, which their authors argued was more likely to indicate the long-run relationship between inputs. Their argument was that if the K for E relationship was one of short-run complementarity and long-run substitutability, then single-nation time-series data could only provide short-run results because of the challenge of estimating statistically significant long-run parameters with so many causal factors. International cross-section data, on the other hand, could proxy as a long period of time series data.

Berndt and Wood (1979) added to the debate by noting that three factor capital, labour and energy (K,L,E) studies tended to indicate K for E substitutability, while four factor (K,L,E,Materials) studies tended to indicate K for E complementarity. The argument was confounded when some four factor studies, notably Turnovesky *et al.* (1982), returned K for E substitutability. Berndt and Wood's argument is somewhat supported by the findings of Frondel and Schmidt (2002), who argue that using a translog approach reduces the issue of factor substitutability to a question of cost shares. The panel comparisons that found substitutability (e.g. Griffin and Gregory) were mainly (K,L,E) as opposed to (K,L,E,M) studies, which Frondel and Schmidt contend is due to a lack of international data on material costs. They argued that (K,L,E) studies will *a priori* raise the resulting elasticities because each of K, L and E will constitute a larger share of production without the inclusion of material costs, and hence are more likely to report substitutability because of the larger shares of the factors.[9]

Helliwell and Chung (1986) continued the latter practice of sub-aggregating capital and energy and introduced another element by including capacity utilization in the production function. This introduced another dimension of potential substitutability between capital and energy. Solow (1987) further argued that price induced changes in the composition of output could cause either complementarity or substitutability in aggregate data, even if no technical substitution is possible, implying elasticities should be measured at the sector level. Substitution in final consumption and changes in the relative incomes of consumers and foreigners were identified as key factors in determining which outcome arises.

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[9] Renou-Maissant (1999) provides an explanation of how factors with small cost shares (<5% as a rule of thumb) will have mechanically induced high price elasticities in absolute value.

There may be a complication with Frondel and Schmidt's argument that not counting material costs when measuring elasticities distorts them. When one looks at national accounts most measured materials costs are processed intermediate inputs, not "raw" unprocessed materials. For this reason, material costs tend to disappear when considering a nation, and disappear completely when considering a complete set of trading partners. This is because value added is counted as the returns to (or expenditures on) the primary factors of capital, labour and land ("land" is more accurately and poetically described by Lipsey as "gifts of nature", e.g. salmon, trees, raw minerals). Material costs to one firm (or nation) are composed of value-added generated by the sequence of firms (or nations) who prepared the material (Lipsey *et al.* 1988, p.175). In a closed national economy there are no intermediate inputs – by definition they exist only if they are imported. Frondel and Schmidt's argument may carry weight when material costs are substantial and if either of the following factors apply: 1) one is measuring elasticities for individual sectors, or 2) one is measuring national elasticities and a large component of material costs are from foreign suppliers. Their argument suffers when one considers that they are criticizing the Griffin and Gregory style cross-panel studies, which are composed to significant extent of trading partners. To the extent that the country samples make up the majority of trade in intermediate inputs, the concept of material costs disappears.

Given the difficulties with econometric analysis of the ESUB parameter, Manne and Richels (1992) approached the problem from the perspective of exploring the sensitivity of GHG emissions reduction and cost estimates to this unknown value. In their simulations with the energy economy model Global 2100, they found that after GDP growth, the capital for energy ESUB is the most important determinant of CO_2 emissions and their cost of reduction in a carbon-constrained future. They used a guesstimated value of 0.4 for the capital for energy substitution elasticity for the OECD and 0.3 for all other nations; the higher value for the OECD is justified by its record of using the price mechanism to decouple energy use and GDP growth. In Manne and Richels (1994) they conducted a probabilistic survey of experts in the field, asking them how much they thought the true value could vary from Manne and Richels' reference case values. They found a mean estimate of 0.464 for the OECD nations, with estimates ranging from 0.2 to 1.0.

Griffin (1977) hypothesized that it may be impossible to calculate the long-run capital for energy elasticity of substitution from past data. He instead used a linear programming model of the US refining industry to calculate the future production possibility frontier by shocking a technology simulation model with a range of prices, and used the resulting outcomes to calculate an econometric production function for that sector. Lack of a technology simulation model that covered the rest of the economy prevented Griffin from expanding his method to the rest of the economy.

2.1.2 The debate over the autonomous energy efficiency index

The second question that emerged from the debates of the early 1970's, the rate at which energy efficiency changes in the long-run independent of changes in the price of energy, or "autonomous energy efficiency index (AEEI)", is effectively a debate over how energy productivity changes over time if relative input prices were to remain constant. It may be defined as:

$$AEEI = \% \frac{\Delta \, {}^{EnergyUse}\!/_{GDP}}{\Delta Time} \tag{2}$$

The importance of the AEEI parameter is evident from the energy policy and climate change literature. Many authors acknowledge that their results are sensitive to this largely unmeasured value (Babiker *et al.* 2001, Manne and Wene 1992, McKitrick 1996). Manne and Richels (1994) addressed the problem by surveying experts to come up with a probabilistic judgment of the AEEI value. They found a mean estimate of 0.70 %/year from mainly top-down modelers. Hogan and Jorgenson (1991) gave a value of 0.3 %/year, while Grübler and Nakicenovic (1996) provided a value of 0.34 %/year. A sample of bottom-up modellers (Williams 1990a) provided a range of higher values (1.5-3.0 %/year), as per their assumptions about the potential for technical efficiency. MARKAL-MACRO's demand side decoupling factors, or DDF, are analogous to the AEEI for the portion of the energy supply system linking energy demand and supply, with the values ranging from 0.25 %/year for electrical appliances to 0.75 %/year for general residential demand (Nyström 1995).

There is an explicit assumption in using the AEEI that its underlying determinants are not affected by the general equilibrium system of prices and demands, which is generally acknowledged as problematic (Grubb *et al.* 1993, Hogan and Jorgenson 1991, Manne and Richels 1992, Williams 1990b, Williams *et al.* 1987). Some observers, including Field and Berndt (1981) and others since, argue that use of the AEEI may be misleading because no efficiency changes occur "autonomously"; all efficiency changes are efforts to conserve scarce resources, in this case to reduce costs incurred from energy purchases. The counter argument is that the AEEI parameter was never meant as an empirically observable stand-alone parameter; it is a catchall term for price induced effects that are too complex to capture completely. Debate aside, the AEEI parameter has allowed modellers to generate results while avoiding the difficult task of explicitly representing the development and deployment of technologies (Babiker *et al.* 2001).

Nyström (1999) provided another perspective on the AEEI. Her primary concern was sorting out the specific origin of energy productivity improvements, specifically those that emerged when prices are fixed. Using a representation of the energy system outlined in Wene (1996), she distinguished between four different contributing phenomena:

- Efficiency improvements within the energy supply system.
- Efficiency improvements on the demand (consumption) side.
- Structural change and autonomous (non-price induced) change in behaviour that decreases energy demand.

- Structural change and autonomous change in behaviour that increases energy demand.

Jaccard *et al.* (1998) and Luciuk (1999) provided another method for estimating the AEEI. Non-priced induced changes in energy efficiency occur mainly through the sequential dynamics of technological development, commercialization, and capital turnover. They demonstrated how one may estimate this parameter by comparing two futures in a technology simulation model, one where technological progress is allowed to proceed normally and one where it is frozen at a base case level. Using this method, Luciuk found an AEEI of 0.69 %/year for a subset of ISTUM demand models for Canada (Industry, Residential and Commercial).

2.2 A survey of models currently used for energy and climate policy analysis

How are AEEI and ESUB used in current models for modelling energy-environment policy? In this section, I report summarized results for a survey of 14 influential models with economy wide capabilities used to model climate change policy. Appendix B provides the detailed results and references for the survey.

2.2.1 The survey sample and questions

The Stanford Energy Modelling Forum (Weyant *et al.* 1999) served as a starting sample of influential energy modelling systems with economy –wide capabilities. With the addition of a couple of key models, the following models were chosen for the survey (Table 1).

Table 1 List of models surveyed

Model Acronym (Full Name)	**Home Institution**
ABARE-GTEM (Global Trade and Environment Model)	Australian Bureau of Agriculture and Resource Economics (ABARE)
AIM (Asian-Pacific Integrated Model)	National Institute for Environmental Studies (NIES-Japan) Kyoto University
G-Cubed (Global General Equilibrium Growth Model)	Australian National University University of Texas US Environmental Protection Agency
MIT-EPPA (EPPA – Emissions Projection and Policy Analysis Model)	Center for Energy and Environmental Policy Research Massachusetts Institute of Technology
MS-MRT (Multi-sector-Multi-Region Trade Model)	Charles River Associates University of Colorado
SGM (Second Generation Model)	Batelle Pacific Northwest National Laboratory
CASGEM	Canadian Department of Finance
McKitrick's estimated CGE for Canada	University of British Columbia / University of Guelph
NEMS (National Energy Modelling System)	Energy Information Administration, US Department of Energy
The MACRO family of models:	
MERGE 3.0 (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	Stanford University Electric Power Research Institute
CETA (Carbon Emissions Trajectory Assessment)	Electric Power Research Institute Teisberg Associates
MARKAL-MACRO	Various, coordinated by ETSAP
MESSAGE-MACRO	International Institute for Applied Systems Analysis (IIASA)

The following questions were asked of each model, with answers provided from published literature and manuals or asked directly of the operators.

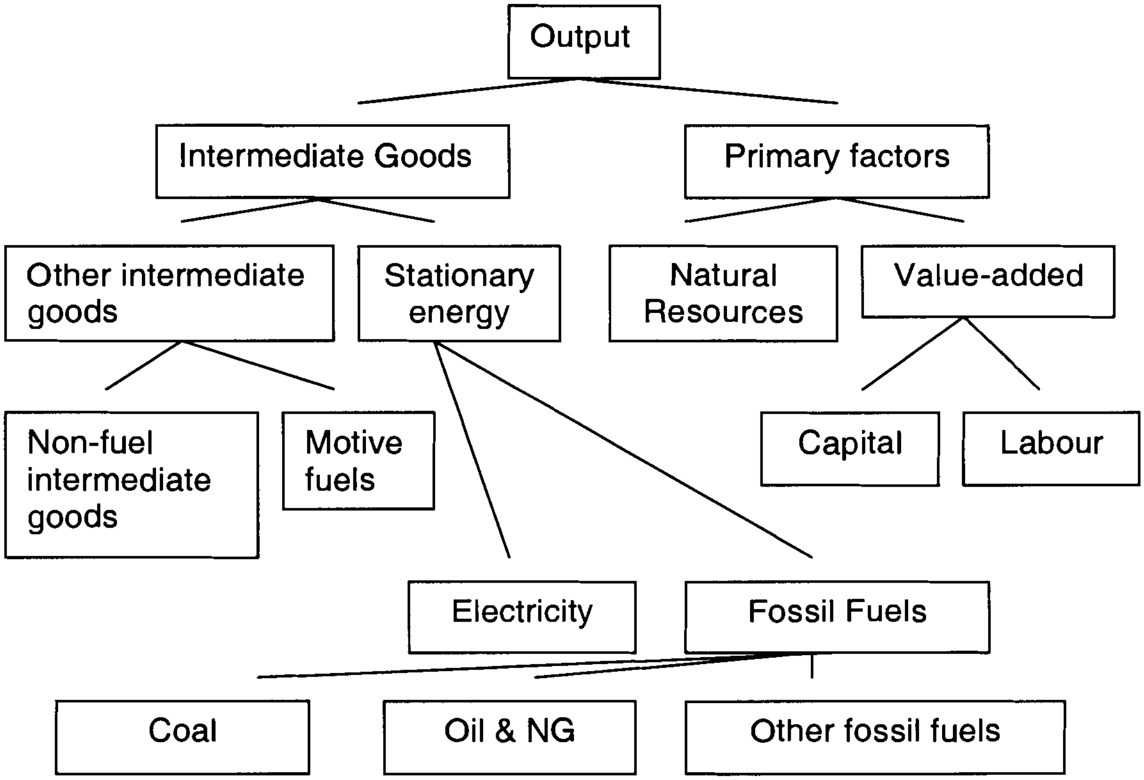
- How does the model accommodate technological change in the short-run (1-5 years), medium term (5-10), and long-run (10+year)?

- If elasticities of substitution are used what are these values and at what level of disaggregation? How are these values estimated (guesstimation, statistical analysis of historical data)?
- Does the model distinguish between different sectors, and if so is technical change handled the same way?
- How does the model handle non-price induced change in input shares (specifically non-priced induced energy efficiency)? If AEEI is used what are the values and at what level of disaggregation? How are these values estimated (guesstimation, statistical analysis of historical data)?
- To what extent are policy impacts on technical change modelled endogenously?
- To what extent, if at all, are policy impacts on producer and consumer preferences modelled endogenously?

2.2.2 Key results of the survey

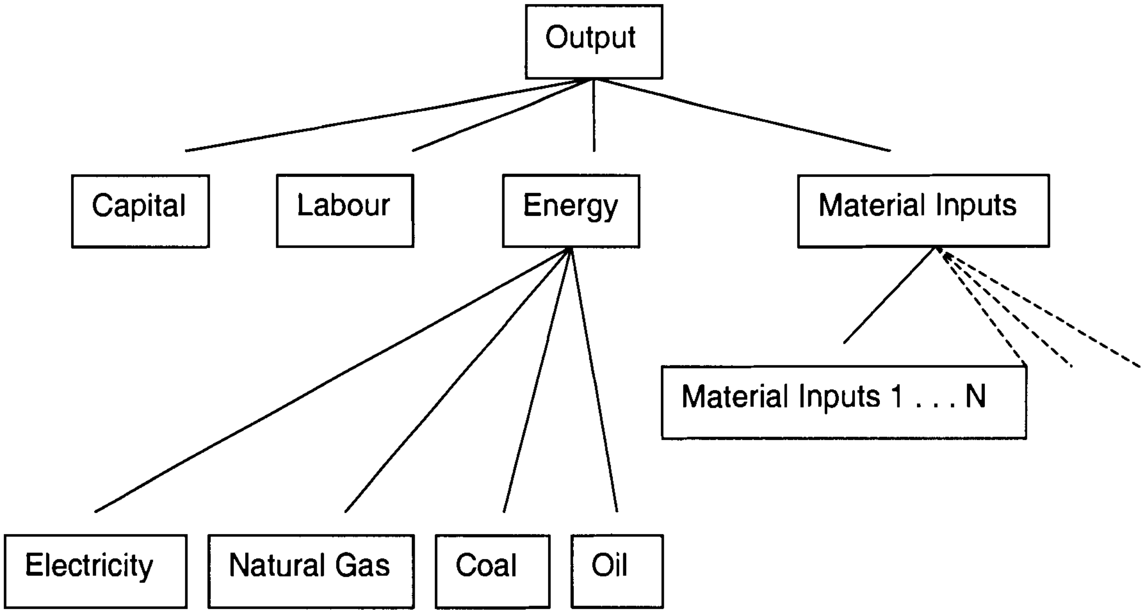
To begin with, the models exhibited considerable variation in production function structure, with consequences for how they portray the substitutability of inputs (ESUB) and modify energy productivity over time (AEEI). Please see Appendix C for a review of common production functions. Four representative types are presented as production function maps (CASGEM, G-Cubed, MIT-EPPA and GTEM). Maps for all the models may be found in Appendix B.

Figure 4 CASGEM



CASGEM (Figure 4) is presented first because it is the simplest in type, if not in structure. Most relationships are depicted with two-input constant elasticity of substitution (CES) functions (e.g. primary factors split into natural resources and value-added, while value-added splits into capital and labour). This method depicts all the substitutability relationships as dual-input relationships, each with their own elasticity, with compound inputs representing lower aggregations of inputs. The only exception is the relationship between coal, an oil and gas aggregate, and other fossil fuels, which uses a multi-input CES that assumes a single substitution relationship between all inputs.

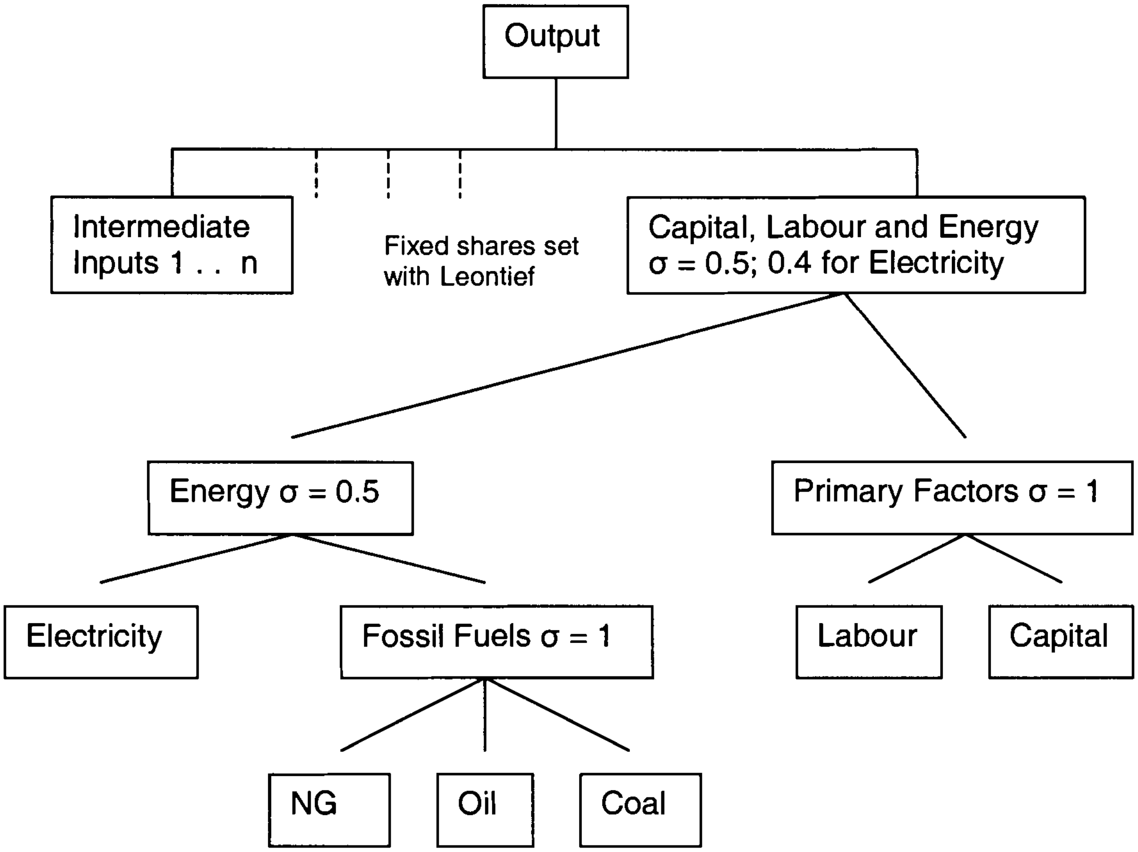
Figure 5 G-Cubed



G-Cubed (Figure 5) differs from CASGEM in that it uses multi-input CES functions widely (e.g. output is split between capital, labour, energy and material inputs, and energy is split between electricity, natural gas, coal and oil). A key difference between G-Cubed and most of the other models is that it is one of the few to make broad use of statistically estimated parameter values. Using the multi-input CES instead of a nested two-input CES function reduces the *number* of relationships to be estimated, as well as reducing the complexity of estimating and proving the nesting structure. One may note that G-Cubed does not make the traditional distinction between primary and secondary energy.

MIT-EPPA (Figure 6) differs from both previous archetypes by using a mixture of Leontief fixed substitutability relationships combined with dual and multi- input CES functions. The Leontief functions are depicted as right-angled lines between nodes, with CES substitution elasticities posted by their nodes. For example, the substitution elasticity is 0.5 for most sectors, and 0.4 for electricity production.

Figure 6 MIT-EPPA



The map in Figure 6 is a general pattern – it differs by sector. MIT-EPPA, SGM and GTEM use Leontief relationships where it is known that the input mixture is fixed, and CES relationships when it is flexible. This process is taken to the furthest extent in iron and steel and electricity production, where the various technologies are substantially different from one another and the ratio of inputs for each technology is fixed; technologies $T_{1...n}$ are competed by minimizing lifecycle costs.

Most of the models use some sort of mix of CES and/or Leontief production functions. NEMS, the only exception, uses a multi-input Cobb Douglas. NEMS' use of a Cobb Douglas in its macroeconomic sub-model, while different from all the other models, may be partly understood in the context that most of NEMS' sub-sectors are quite technologically disaggregated; the substitutions between inputs occur at this lower level.

There are also differences in the degree of sectoral disaggregation in the surveyed models, again with implications for how ESUB and AEEI are handled. Steel and paper production have very different mixes of inputs, outputs and emissions; their responses to energy efficiency and emissions reductions policies are likely to be quite different. When one is doing global analysis, a high degree of disaggregation may be both burdensome and unnecessary. However, if one is primarily interested in emissions and energy consumption, and hence energy price dynamics, disaggregation amongst industries with differing energy consumption characteristics is desirable. In addition, without sectoral disaggregation the ability to depict structural adjustment is limited.

SGM, MIT-EPPA, G-Cubed, GTEM, CASGEM, NEMS, and McKitrick's CGE all have a relatively high degree of sectoral disaggregation. MIT-EPPA and McKitrick most closely tailor their production functions to the individual sectors. MARKAL-MACRO is highly disaggregated for energy production and consumption, with the rest of the economy gathered into a single nested compound CES function. MERGE (and CETA by proxy), a composite of ETA and MACRO, has the least amount of sectoral disaggregation; ETA is an energy resource supply model while MACRO is a simple aggregate production function.

The degree of production function nesting is also significant, especially when using the CES function. By definition, the CES forces a single fixed elasticity of substitution amongst inputs at a given level of aggregation. Consider the case where the substitution elasticity between capital and labour is 1, and that between capital and energy is 0.5. If they were all on a single level with an elasticity of 1, the substitutability of K and E would be overstated. The nesting solution is to nest K and E together at 0.5, and nest that composite input against L at 1. It might be acceptable to nest K and E if we think of using energy to run machinery, and substituting this with labour. To explore this relationship McKitrick (1998) based his production function nesting on statistical analysis. However, because his nesting pattern is different from that of the other modellers, it is difficult to compare his results to theirs.

The elasticity values, the relationship between capital and energy in the production function and the ESUB parameter sources are summarized in the Table 2. See Appendix B for details.

Table 2 Summary of the relationship between capital and energy in the various models

Model	Relationship between Capital and Energy	Parameter Source
SGM	All inputs nested at the top-level with a CES production function. Short-run elasticity of 0.1 for all sectors except electricity, refining and gas distribution (0). Long-run elasticity is 0.28 for all but electricity, refining, and gas distribution (0.1), agriculture (0.3), services (0.4).	A mixture of values from the translog literature and guesstimation.
MIT-EPPA	The top-level relationship is a Leontief production function (fixed) between intermediate inputs and capital, labour and energy. At the second level it a uses a CES production function with (K, L) vs. energy at an elasticity of 0.5, 0.4 for electricity.	A mixture of values from the translog literature and guesstimation.
GTEM	Unknown – no response from operators	"
G-Cubed	Top-level CES with capital, labour and energy and materials sub-nests. Top-level elasticities range from 0.2556 to 1.703; estimated elasticities in the energy nest range from 0.1372 to 1.14. Several sectors had nonsensical values that were replaced with 0.2 (electricity, refining and transportation).	All top- level elasticities are estimated, with some 2nd level nonsensical values replaced with guesstimates.
AIM	The top-level relationship is a Leontief production function (fixed shares) between intermediate inputs and capital, labour and energy. At the second level it a uses a CES with (K, L) vs. energy at an elasticity of 0.2-0.5 depending on the country.	Expert guesstimation.
MS-MRT	The top-level relationship is a Leontief production function (fixed) between intermediate inputs and capital, labour and energy. At the second level it a uses a CES with (K, L) vs. energy at an elasticity of 0.25-0.5 depending on the country.	Expert guesstimation.
MERGE, MARKAL-MACRO & CETA	CES, K/L vs. E ESUB = 0.4, 0.3 for CETA	Expert guesstimation.
McKitrick	The top-level is a CES, usually non-energy vs. energy. Non-energy breaks down into various sub-components that usually include capital and labour. Manufacturing = 0.23, Services = 0.09, Mining =1.15, Utilities = 0.15, Refining =0.	Most elasticities are estimated, with some nonsensical values replaced with guesstimates.
CASGEM	The relationship between energy and the primary factors is indirect; energy is treated as an intermediate good. CASGEM first substitutes primary and intermediate goods, and then stationary energy and other intermediate goods, and finally on the third level non-fuel intermediate goods and motive fuels as well as splitting stationary energy between electricity and fossil fuels.	Based on the Canadian econometrics literature and Natural Resources Canada's Interfuel Substitution Demand model.
NEMS	Cobb Douglas with 4 inputs (σ =1): labour 64% of the cost of production, private capital, 26%, government capital 2%, energy 7%.	NA

The ESUB parameters in the MACRO family of models are all guesstimated, as are the parameters for AIM and MS-MRT. SGM uses a mix of estimated parameters from literature translog models and guesstimated parameters when these are not available. MIT-EPPA follows much the same approach, with a heavier emphasis on literature values. As a mixed CGE-econometric model, G-Cubed's parameters are mostly statistically estimated, with a couple of exceptions where results suggest extreme magnitudes or wrong signs when the complementarity versus substitutability relationship is clear, etc. In these cases, the modellers impose a guesstimated elasticity; key amongst these is the electricity sector. McKitrick's values are mostly statistically estimated. CASGEM's elasticity values come from the Canadian economics literature and Natural Resources Canada's Interfuel Substitution Demand model. As a hybrid, much of NEMS' factor substitution occurs at the technology level, which means that its Cobb-Douglas coefficients do not represent the full substitution response between factor inputs. Despite several attempts to contact the GTEM modellers, it was unknown at time of writing how GTEM establishes its AEEI and ESUB parameters.

The wide divergence in method reflects several challenges. It is difficult to get data for estimation, and even then, the results are vulnerable to the method, specifically the production function used. Finally, the modeller will not necessarily get a significant relationship due to lack of variation in the data or a lack of direct causality. These difficulties mean that more than half the models depend almost entirely on expert guesses and subsequent sensitivity analyses for their key parameters.

The models accommodate non-price induced input efficiency increases differently, if at all. Table 3 summarizes the treatment of energy productivity in the models that have an explicit method. See Appendix B for details.

Table 3 Treatment of energy productivity over time

Model	AEEI (%)	Notes
SGM	NA	Used for calibration
MS-MRT	NA	Used for calibration
MIT-EPPA – US Note: AEEI for all MIT-EPPA is applied as a logistic; efficiency growth gradually slows over time as producers exhaust the technical potential for saving energy. Primary energy sectors do not experience AEEI.	1.301	Sourced from expert elicitation and reviews of other climate policy work
MIT-EPPA - Other OECD	1.210	"
MIT-EPPA – China	1.980	"
MIT-EPPA – India	1.430	"
MIT-EPPA – ROW	1.100	"
G-Cubed	1	
MERGE	0.5	Guesstimated
CETA	0.25	Guesstimated
MARKAL-MACRO (DDF) Residential	0.75	Guesstimated
MARKAL-MACRO (DDF) Commercial	0.5	Guesstimated
MARKAL-MACRO (DDF) Elec. Appl.	0.25	Guesstimated
McKitrick	0.5	Guesstimated, cited as a standard literature value by author

Some modellers, including SGM and MS-MRT, have used their input efficiency parameters, including that for energy, as a calibration factor to match official government forecasts and/or apparent divergences between output and energy inputs. NEMS, CASGEM, and AIM do not mention use of an AEEI, but it is likely that they incorporate input efficiency parameters to calibrate to energy or emissions data.

The AEEI does not lend itself to easy estimation from historical data, mainly because it is not price induced. There is no obvious independent variable upon which it depends; instead, time is usually regressed against energy use per unit of GDP in a given sector. This requires good coverage of all other variables that may influence energy use in a given time period, otherwise a portion of the energy input productivity increases due to some other cause (such as the cost of energy and its substitutes) may be improperly assigned to the time variable. This leads all the models to use a guesstimation approach to the AEEI.

A significant point made by Nyström (1995) is that the more of the energy system you capture with explicit technologies, the smaller the non-price induced factor is likely to be. If your set of energy using technologies is complete and if the model is structurally disaggregated, a separate AEEI parameter is not necessary, as the gradual evolution of the technology stock will account for all non-priced energy efficiency changes. The representation of capital stock turnover is therefore an important factor.

The models treat capital stock turnover differently. Models that depict capital stock turnover explicitly are SGM, MIT-EPPA, MERGE, MARKAL-MACRO, MACRO-MESSAGE, G-Cubed and NEMS. SGM and MIT-EPPA include it by fixing the input ratios for older stock using Leontief production functions, after allowing the ratios to be set using a CES equation when the capital is acquired.

G-Cubed allows a mixture of fixed short-run capital (Leontief fixed ratio equations) and variable long-run capital (CES variable ratio equations). It is unknown how capital vintaging is handled in GTEM but due to its similarity to SGM and MIT-EPPA it is likely that it is handled in a similar fashion. Most of the MERGE and the MACRO models directly track stock vintages – CETA's operators, who removed the vintaging feature to simplify the model, explicitly increased the ESUB and AEEI parameters to make their results similar to that of CETA's predecessor, MERGE. NEMS, as a bottom-up model wedded to a macroeconomic module, accounts for capital vintaging within its individual sectors. This depiction is most explicit in electricity and transportation, and least explicit in the industrial, residential, and commercial sectors. McKitrick assumes that the effects of capital stock turnover are captured by his statistically estimated parameters for ESUB and AEEI. The AIM model's documentation is puzzling in that it accounts for neither an AEEI nor direct capital vintaging. CASGEM does not seem to use an over time efficiency adjustment. MS-MRT uses explicit vintaging, and while it allows previously installed capital to adjust within sectors, it is not allowed to move across sectors.

The key finding is that in most of the models the majority of key parameters are guesstimated, as opposed to statistically estimated from historic data. Statistical estimation of parameters using historic data grounds the parameters in observed behaviour, a point that is important to many analysts. There are limitations to this method, however, in that the parameters reflect not only the data, but also the functions that were used to estimate them. Also, it may be argued that past behaviour does not provide a good indicator of future behaviour, and that significant discontinuities in behaviour and technology would invalidate parameters based on historical data.

Mckitrick (1998) makes the argument that estimated generalized production functions, such as the translog and generalized Leontief, would more accurately portray the (non)-substitutability of inputs than a calibrated CES, the common practice. In the calibration method, some parameters are determined on the basis of a survey of empirical literature, some are chosen arbitrarily, and the remainder are set at values which force the model to replicate the data of a chosen benchmark year (Shoven and Whalley 1992). Generalized production functions instead incorporate parameters that allow the substitution elasticities to change with different input prices and cost shares. The difficulty of finding statistical significance when estimating parameters from time series data (stationarity tests, etc.) and calibrating generalized functions has pushed modellers toward using CGE models with calibrated CES functions, rather than estimating generalized ones. Of the 14 models surveyed, only G-Cubed, CASGEM and McKitrick's model for Canada used statistically estimated ESUBs, while none used estimated AEEI. The documentation for all three suggests difficulties in finding the required data and the necessity of occasionally using guesstimated values. Were a better method available to estimate parameters for generalized functions it may become more feasible to use them in CGE models.

2.3 Research questions

The literature review and survey of leading energy-economy models highlight some of the major challenges facing policy modelling of GHG abatement. More aggregated and therefore abstract representations of the energy system, as in the production functions of CGE models, are able to summarize the economy's ability to respond to price-focused policies with just a couple of key parameters, namely ESUB and AEEI. But at this aggregate level, with what confidence are these parameters determined and even if there is considerable confidence in empirically estimated historical values, what confidence can policy-makers have in their application to forecasting the response to future policies?

These parameters are meant to indicate long-run trends: the long-run response to a change in relative input prices and the long-run tendency of energy productivity in the absence of changes in relative prices. The literature review showed that empirical estimates of these parameters from real-world data have been disputed since the oil-price shocks of the 1970s. The full long-run response to a price change is difficult to detect if there is minimal relative price change, or if the relative price changes reverse themselves before the full response can be realized. Econometricians have used various methods to detect the long-run response from incremental changes over shorter time periods, but this has not always proved satisfactory. Even if empirical estimates seem to be robust in portraying historical relationships, there is suspicion that these values might not be appropriate for simulating the future depending on the effect of pricing policies and policies directed at specific technologies through regulation, subsidies and support for innovation. These two challenges – empirical estimation of long-run parameters and suspicion that historically derived parameters might not reflect future response – has led many modelers to set some or all of these parameters judgmentally.

A critical research direction, therefore, is to test for the appropriateness of these parameters for simulating the future response to policies. A research question I seek to answer in this thesis is:

"Question 1: Can I develop an alternative, defensible means of estimating the ESUB and AEEI parameters for top-down, CGE models that provides a check on the guesstimated and highly uncertain values that are commonly used?"

As described in the literature review, Griffin (1977) suggested that a bottom-up model could be price shocked in order to generate "pseudo data," the artificial data set of model outputs for a range of input values. This data could then be subject to statistical estimation of the ESUB and AEEI parameters using a flexible form of the production function. Even a relatively simple, static form production function would provide long-run estimates of parameter values if the pseudo data represents the response over a lengthy time period (e.g. 20 – 30 years). However, Griffin's bottom-up model was a linear programming model of the US petroleum refining industry. Jaccard *et al.* (1996) suggested that one might replace Griffin's linear programming model with a hybrid model that includes technological explicitness and behavioral realism for all demand sectors of the energy-economy. In earlier research (Bataille 1998) I applied this approach to estimating ESUB parameters to a demand side version of a hybrid model called ISTUM. Luciuk (1999) applied it to estimate the AEEI parameters of the same model.

The parameter values from this research are not, however, of use for direct comparison with the ESUB and AEEI parameters in CGE models because they represent only the energy demand side of the energy-economy system. In this thesis, I link hybrid energy demand and energy supply modules to estimate these parameters for an integrated energy supply-demand model. This allows me to explore an ancillary research question of importance to CGE modelers:

"Question 2: Will my estimated ESUB and AEEI parameters be significantly different from one sector (iron and steel production, residential housing, etc.) of the economy to the other? If so, to what extent does this indicate that different evolutionary paths of economic structure would lead to different future ESUB and AEEI values, and therefore different responses to energy-economy policies such as GHG abatement?"

The results of this research would be of considerable interest to CGE modelers. But their models need one more piece of information for a full comparison between aggregate CGE parameters and the parameters estimated from the pseudo data generated by a hybrid model. They need to know the extent to which the demand for energy services and products in different sectors of the economy would be affected by GHG abatement policies. The hybrid model also needs, therefore, to indicate this macro-economic response to policies that change the costs of energy commodities and energy-related technologies. This leads to the research question:

"Question 3: To what extent will my estimated ESUB and AEEI parameters differ once the full macro-economic response to policy is included?"

The answer to this research question provides an alternative value for comparison with the values currently used in CGE models, but the comparison is not a trivial exercise because CGE models vary in their degree of disaggregation and representation of the aggregate production function. Therefore, in addition to providing ESUB and AEEI values from simulating an integrated, energy-economy hybrid model, I apply the model to a final research question:

"Question 4: What GHG abatement cost curves result from the simulation of an energy-economy hybrid model, and how might these compare to cost curves developed by other CGE and bottom-up modelers?"

To answer this question, I conduct a full GHG abatement costing exercise with the hybrid model I construct. This includes the simulation of GHG taxes (or permit prices) for the following cases: sectors without feedbacks; integration of energy supply and demand; and integration of energy supply-demand with macro-economic feedbacks in the form of energy trade responses and shifts in the demand for domestically produced goods and services and energy commodities.

Chapter 3 answers research question 1, and provides the means for answering question 2, 3 and 4, whose results are presented in Chapter 4, the results section. In Chapter 4 sections 4.1, the AEEI results, and 4.2, the ESUB results, address research questions 2 & 3. Section 4.3, the cost curves results, addresses question 4.

3 Methods & Data

The purpose of this chapter is to introduce the suite of methods used to answer my research questions. It is followed by a results chapter that describes the detailed outputs, a discussion chapter about how well CIMS met its design criteria and the ramifications of the results, and a concluding chapter that assesses the thesis project and provides future direction.

This chapter begins with a description of the theory and criteria used to create the CIMS hybrid model by integration of the pre-existing ISTUM sector sub-models using a system of micro and macro economic feedbacks. It is followed by description of the methodology used to calculate the AEEI and ESUB parameters, as well as how effects of the CIMS' feedbacks mechanisms were assessed. It finishes with a description of how cost curves of GHG emissions abatement were created, and they were used for GHG policy analysis.

3.1 The theory and criteria used to build a hybrid equilibrium model

Inclusion of equilibrium feedbacks in a hybrid model makes it capable of simulating the structural change effects of a policy, where structural change is the reallocation of the productive resources of the economy in response to changes in demand generated by policy actions. Loulou and Kanudia (2000) divide structural change into direct and indirect components.[10] Direct structural change occurs when changes in the cost of production lead to changes in prices for goods and services, and thus a change in their relative demand. Indirect structural change occurs when direct structural change has significant consequences for disposable income and savings (multiplier effects), currency exchange rates, government spending, employment and wages, and thus has subsequent effects on the direct effects.

Loulou and Kanudia were concerned with whether a "partial" endogenization of the macro economy (direct structural change), or a "full" endogenization with indirect structural change, is necessary to conduct GHG policy analysis. Based on the assumption that "partial" endogenization is sufficient, they detailed a GHG policy modelling project to use North American MARKAL to cover production, consumption and trade and an existing macroeconomic model to cover the effects on wages, government expenditures and labour. MARKAL is run first; its results are then used to run the macroeconomic model. Their stated assumption in not rerunning MARKAL including the effects of the macroeconomic model is that most of the effects of a GHG policy are likely to be direct structural change, and that the indirect structural change effects will have little effect. In support of this they cite Schreper and Kram (1994), who found that if a 50% GHG emission reduction imposed on the Netherlands was modelled with MARKAL-MACRO, 84% of emission reductions would be due to changes in GHG intensity, 13% to structural changes in demand for energy using goods and services, and 3% to

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[10] The terminology they used was "first and second order macroeconomic effects."

indirect structural changes. Loulou and Kanudia acknowledged that the necessity of "partial" versus "full" endogenization was unresolved, however, and in an attempt to catalogue the effects and thus sort out the problem, they provide the following list of main macroeconomic variables likely to be affected. These variables are provided with a brief discussion of the possible feedbacks effects related to a GHG policy.

Domestic production of goods and services – Depending on the sector and how the policy is implemented, a GHG policy is likely to raise the cost of production for a good or service and thus, depending on the elasticity of demand, lower the quantity demanded.

Trade – In the same vein as above, if a region faces a new set of input prices (e.g., a GHG charge is added) trade patterns may change. The result depends on all participants' relative propensity to import and export.

Total expenditure by households – The effects of GHG policy depend on the substitutability of inputs to firms and final outputs to domestic and foreign consumers. Total expenditure by households is a function of prices, the propensity to import, labour and capital income, and the propensity to consume, work and save.

Government revenue and spending – Government revenue is principally a mixture of income and sales taxes. The effect of GHG policy is thus a function of its effects on labour income and domestic economic activity. It also depends on how the GHG policy is implemented (subsidies, tax, permit trading system), and how the revenue is used (to reduce other taxes or increase spending).

Wages and/or employment - Labour income depends on the net effect of GHG policy on production of labour intensive goods and services.

Savings by households – Savings, the primary source of domestic capital formation, is a function of labour income, prices, the discount rate and the propensity to save and work.

The cost of capital – The cost of capital depends on its supply and demand. It is the equilibrium of desire to borrow it for investment or consumption and to lend it out for a return. GHG policy can have effects on both sides of this equation – GHG policy may both increase the demand for investment in different and more efficient capital stock, and possibly raise the domestic price of capital through scarcity effects.

Gross domestic product – The effects on national economic activity are an amalgam of all of the above.

Loulou and Kanudia's study, along with the literature review from Chapter 2, was influential in helping me set the following design criteria for CIMS, the new hybrid equilibrium model. It also prompted me to conduct an analysis similar to Schreper and Kram's in order to shed some light on value of "full" versus "partial" endogenization. I return to their conclusions about the relative importance of direct and indirect structural change in the discussion chapter.

3.1.1 Criteria for choosing methods to build a hybrid equilibrium model

The following criteria were used for choosing methods to build the hybrid equilibrium model:

1. The methods should be able to simulate equilibrium between energy supply and demand when goods and services demand is considered to be exogenous.
2. The methods should be able to simulate equilibrium between supply and demand for goods and services that consume significant amounts of energy.
3. The methods should be able to simulate export and import substitution effects for a highly trade dependent economy such as Canada's.
4. The methods should be able to simulate and track investment and capital formation.
5. The methods should be able to simulate savings, labour market, and disposable income effects.
6. The methods should allow a wide range of scenarios, including testing of alternative assumptions (e.g., Canada as a price taker for the cost of capital, the ongoing dominance of US trade for Canada, full flexibility in the turning on and off of individual portions of the feedbacks systems).
7. The macro-economic equilibrium of the model should not depend on models for which access would be expensive and restricted.
8. Data requirements of the model should mostly be limited to regularly available data sources or data that can be estimated from relatively modest surveys.
9. The design of the model should be as simple, maintainable, and flexible as possible given all its other requirements.

10. The design of the model should accommodate the underlying ISTUM sub-models, which have seen 15 years of development.

3.1.2 A review of previous methods to add economic feedbacks to bottom-up simulation models

Prior to construction of CIMS, I conducted a review of previous projects to add economic feedbacks to a technology simulation model. These methods were compared to the criteria established in the previous section.

Basic MARKAL – The physical production, flows and pricing of energy commodities responds to policy; in other words, supply and demand systems are created for various energy commodities. Basic MARKAL operates using linear optimization (Fishbone and Abilock 1981, ETSAP 2003).

MARKAL Elastic Demand (ED) - Final demand for selected energy services responds to the price of providing these services (Loulou and Lavigne 1996). These elasticities seem to have been mainly guesstimated, due to a lack of estimated values that correspond exactly to the products in the MARKAL model.

MARKAL North America - Canadian MARKAL with 7 regions for Canada and 1 region to simulate Canada's trade with the United States Loulou and Kanudia (1999).

MARKAL MICRO - Service demand elasticities were applied for selected products while selected inter-sector demand substitution equations were applied based on consumer utility maximization. The primary object of this project was the endogenization of transportation mode demand (ETSAP 2003).

MACRO MARKAL - MARKAL was linked directly with a simple Keynesian growth model (MACRO) with a CES production function that allows substitution between energy, capital and labour (Manne and Wene 1992). MARKAL is linked to MACRO through AEEI values, also called demand-decoupling factors. These decoupling factors link the energy service demand from MACRO to the energy services being delivered by MARKAL, and are meant to represent energy productivity changes not captured in MARKAL, within the context of its use with capital and labour.

15 Region MARKAL with Elastic Demands – 15 different MARKAL models from around the world are brought together in a hard-linked format. This linkage allows trading of energy commodities and emissions permits. Demand for energy services (goods and services produced with energy) is adjusted using own-price elasticities for the goods and services (Labriet *et al.* 2004).

MACRO MESSAGE III/IV - MESSAGE is soft linked with MACRO (the parameters are passed manually), the same CES model used for MARKAL-MACRO (Wene 1996).

National Energy Modelling System (NEMS) (USDOE/EIA 2004) - NEMS is a disaggregated technology simulation model, with different degrees of explicitness and modelling methods for differing sectors. A couple of different macroeconomic methods have been used with NEMS. It started with a system of demand elasticities to account for cost of production changes. This system was unsatisfactory because demand did not “rebound” after a policy, as one would expect when a sector gradually adjusts its methods of production to a policy, lowering its cost of production, decreasing its price, and thus recovering its market share. This kind of response requires that the capital stock adapt to policy, and NEMS' picture of technological turnover is not uniformly sophisticated enough to do this. This prompted the operators to switch to a set of econometric equations (kernel regressions) that imitate the responses of a more complex macro econometric model for a given range of input prices.

This provides us with eight established methodologies for adding economic feedbacks to a technology simulation model:

- Integration of energy supply costs with production volumes.
- Addition of a system of energy service demand elasticities to adjust the demand for energy services based on changes in price.
- Addition of international trade in energy commodities and goods through multi-region modelling.
- Addition of a system of inter-sector demand substitution using cross price elasticities.
- Addition of a simple global demand adjustment.
- Soft linking (manual passing of data and parameters between models) with an established macro model using a reference energy system.
- Hard linking (automated passing of data and parameters between models) with an established macro model.
- Use of partial elements of established macroeconomic models.

The following sections describe how economic feedbacks were added to ISTUM, using both previously established and new methods. For these methods to make sense, however, the reader requires some background on the structure and function of the ISTUM sub-models.

3.1.3 The building blocks for CIMS: The ISTUM sub-models

I constructed the CIMS hybrid energy-economy equilibrium model by integrating the pre-existing Canadian Inter Sectoral Technology Use Model (ISTUM) sector sub-models into a framework of micro and macro economic dynamics. ISTUM was developed and maintained by the Energy and Materials Research Group at the School of Resource and Environmental Management at Simon Fraser University. EMRG is closely associated with the Canadian Industrial Energy End Use Data Analysis Centre (CIEEDAC), an arms-length data analysis agency funded primarily by Natural Resources Canada. Much of ISTUM's data was collected initially for CIEEDAC, which reviews data annually in collaboration with the Natural Resources Canada, Statistics Canada and industry associations. EMRG now provides the institutional home for CIMS. A summary of ISTUM's structure, data and dynamics precedes the methods used to integrate the sub-models.

The ISTUM sub-models can be separated into the following categories: primary energy supply, energy processing, and end-use demand for energy services (Table 4).

Table 4 A taxonomy of the ISTUM sub-models

Primary Energy Supply	Energy Processing	Demand models	End-uses of demand models[11]
Natural Gas Extraction & Transmission	Refined Petroleum Products Production	Commercial/Institutional (Government, retail, office space, hospitals, schools, etc.)	Refrigeration, cooking, hot water, plug load
Coal Mining	Electricity Production	Transportation	Freight, personal and Offroad km
Petroleum Crude Extraction & Transmission		Residential	Refrigeration, dishwashers, freezers, ranges, clothes dryers, clothes washers, other appliances
		Iron and Steel	Slabs, blooms and billets
		Pulp and Paper	Newsprint, linerboard, uncoated and coated paper, tissue and market pulp
		Metal Smelting	Lead, copper, nickel, titanium, magnesium, zinc and aluminum
		Chemical & Petrochemical Production	Chlor-alkali, sodium chlorate, hydrogen peroxide, ammonia, methanol, polymers
		Mining	Open-pit, underground and potash
		Industrial Minerals	Cement, lime, glass and breaks
		Other Manufacturing	Food, tobacco, beverages, rubber, plastics, leather, textiles, clothing, wood products, furniture, printing, machinery, transportation equip., electrical equip., electronic equip.

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[11] Most also include space heating, air-conditioning and lighting

An ISTUM simulation involves five basic steps:

Assessment of demand: Technologies are represented in the model in terms of the quantity of service they provide. This could be vehicle kilometres travelled, tonnes of paper, or metres squared (m^2) of floor space heated or cooled. A forecast is then provided of growth in energy service demand.[12] This forecast drives the model simulation, usually in five year increments.

Retirement: In each future period, a portion of the initial year's physical capital stock is retired. Retirement depends only on age.[13] The residual technology stocks in each period are subtracted from the forecast energy service demand and the difference between demand and available stock determines how much new stock is to be purchased (i.e. gross investment).

Retrofitting: Existing stock is assessed for retrofit possibilities that may save overall costs; complete replacement of the functioning stock with new stock is possible in some cases if conditions warrant. The retrofit competition uses the same functions as for new demand (see below).

Competition for new demand: Prospective technologies compete for necessary new investment. The objective of the model is to simulate this competition so that the outcome approximates what would happen in the real world. The

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[12] The growth in energy service demand (e.g., tonnes of steel) must sometimes be derived from a forecast provided in economic terms (e.g., dollar value of output from the steel sector). This opens the question of how the price of a given quality of product may change over time. This value is assumed to be covered by the cost of production in this exercise, i.e. price equals average or marginal cost. See Nanduri (1998).

[13] There is considerable evidence that the pace of technology replacement depends on the economic cycle, but over a longer term, as simulated by CIMS, age is the most important and predictable factor.

following equations depict CIMS' simulation of the technology competition when new equipment stocks are required, as a function of *life-cycle-costs* designed to mimic real investment behaviour.

$$MS_{kt} = \frac{LCC_{kt}^{-v}}{\sum_{j=1}^{J} LCC_{jt}^{-v}} \tag{3}$$

MS_{kt} = market share of technology *k* for new equipment stocks at time t,
LCC_{kt} = annual life-cycle-cost of technology *k* at time t,
v = variance parameter representing cost homogeneity,
j = technologies competing to provide the same service as *k*.

The MS_{kt} function is a logistic curve whose slope is determined by a *variance parameter*, *v*. A high value for *v*, such as 100, means that the technology with the lowest life-cycle-cost captures almost all of the new equipment stocks, as would occur with a linear programming model. An extremely low value for *v*, such as 1, means that new equipment market shares are distributed almost evenly between all competing technologies, even if their life-cycle-costs differ significantly. Thus, *v* represents sensitivity of the technology competition to relative life-cycle-costs.

Life-cycle-costs of an individual technology, *k*, can be defined as annualized capital costs (up-front costs) divided by annual output, plus the per-unit, non-energy and energy annual operating costs.

$$LCC_{kt} = \left(\frac{CC_{kt} \times \dfrac{r}{1-(1+r)^{-n}}}{SO_k} \right) + O_{kt} + E_{kt} \tag{4}$$

CC_{kt} = capital cost of technology k at time t,

SO_k = annual service output of technology k,
O_{kt} = operating cost (non-energy) of technology k at time t per unit of service output,
E_{kt} = energy cost of technology k at time t per unit of service output,
r = technology specific competition discount rate[14]
n = equipment lifespan

The CIMS user can specify a different value for *r* for every technology competition and capital costs can be defined to include an *intangible cost*, *i*, that represents estimated option value costs and/or consumers' surplus losses associated with a technology relative to its prime competitor.

$$CC_{kt} = FC_{kt} + i_{kt} \tag{5}$$

FC_{kt} = financial cost of technology k at time t
i_{kt} = intangible cost factor of technology k at time t

The higher the value for *r*, the greater the competitive disadvantage for technologies with a higher capital-to-operating-cost ratio. The higher the value of *i*, the greater the competitive disadvantage for a technology.

These three equations characterize in general CIMS' simulation of the technology competition for new equipment stocks, but there are other functions and constraints.

- Service demands are in a hierarchy in which demand for lower level services are a linear function of the demand for higher services, linked in a *service flow model*.[15] Total steam output in pulp and paper mills depends on the aggregate steam required by all pulping technologies.

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[14] Please note "r" is not the social discount rate or the financial cost of capital, but the latter plus a premium to account for sector or firm specific risk and lost (quasi) option value. The visible outcome of this are the 2-5 year paybacks typical of such decisions.

[15] This is comparable to the *reference energy system* in an integrated optimization model.

- A *maximum* or *minimum market share* constraint can be applied to any technology. A maximum market share for natural gas space heating ensures that this technology does not penetrate beyond the plausible extension of the natural gas distribution system.
- A *declining capital cost* function, if activated, links a new technology's capital cost in future periods to its achieved market share in the previous period. This allows the user to apply information on the relationship between a new technology's production levels and the evolution of financial costs and consumer and business preferences. The parameter values of this function can be based on previous experiences with comparable technologies.

The parameters *v*, *r* and *i* are critical to the simulation of technology competition, especially with respect to the definition of cost. To replicate the bottom-up approach, *v* would be set at 100 (winner-take-all), *r* at the social discount rate and *i* at zero, ensuring that the technology with the lowest financial cost (at the social discount rate) captured all new technology stocks. In addition, the macro-economic module would be de-activated if the intention were to reproduce the partial-equilibrium perspective of most bottom-up analysis.

With a hybrid model such as CIMS these three parameters must characterize the estimated real world preferences of consumers and businesses, and the potential for these preferences to evolve under certain policies. As a forward-looking exercise, this estimation process inevitably involves a great deal of uncertainty.

For setting *v*, the general approach has been to ask experts for a range of values that can be tested by sensitivity analysis. The default value for *v* is 10, meaning that where a technology has an *LCC* advantage of at least 15% over its competitor(s) it would capture at least 80% of new stock.[16]

For setting *r* and *i*, users of CIMS review the literature on discrete choice research that estimates the revealed and stated preferences of consumers and businesses for certain technology attributes, namely time preference for *r* and other qualities like consumers' surplus for *i*. Table 5 shows key technology competition nodes default values for *r*, as derived from the literature.

Table 5 Default discount rates in CIMS[17]

Sector	*Technology*	*Range (%)*	*Discount Rate (%)*
Commercial	Building HVACs	30-50	20
	Cogeneration		25
	Other		30
Residential	Space heat / Shell	26 - 79	35
	Refrigeration	61 - 108	65
	Other appliances	30 - 70	35
Industrial	Process	20 - 50	35
	Auxiliary	>50	50
Electricity	Generation		20
Transportation	Private vehicles		30
	Buses outside urban areas		12.5
	Urban public transit		8

The default value for *i* is zero. However, there are numerous cases in which discrete choice research suggests a specific value for *i*, as when comparing new vehicle technologies to conventional ones (Bunch *et al.* 1993). In addition, *i* is sometimes used as a calibration parameter for energy consumption.

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[16] Our research group is currently reviewing market research that shows how cost sensitivity varies by type of decision-maker (business vs. consumer) and even by income. In future, we expect to use a slightly higher value for the industrial, energy supply and freight transportation sectors, and a slightly lower value for decisions by final consumers.

[17] For the sources for all estimates see Nyboer (1997) and Train (1985).

Output: Output is provided for total capital stock, new capital stock, fuel use, service use, emissions and levelized costs by technology. The references, data and data sources of each of the ISTUM sub-models evolve as better and more resources become available; see Nyboer (1997) for the general ISTUM method and the EMRG's website for ongoing updates to the CIMS model documentation.[18]

By using the ISTUM sub-models as the basic building blocks of the hybrid model, some potentially limiting characteristics were inherited from the ISTUM framework. The main issue is the aggregation and coverage of the sub-models. All models simplify the real world system they represent. Dedicated economic models will concentrate on providing detailed information on sectors with the greatest value-added, such as manufacturing, while dedicated labour analysis models will provide the greatest detail on those sectors with the greatest number of jobs, such as services and finance. ISTUM started out as an energy policy analysis model. The sector coverage of the ISTUM sub-models (e.g. Industrial Minerals covers cement, lime, glass and brick production) is based on the available aggregations of data, how much energy a sector uses and the similarity between sectors in terms of their energy using equipment. Hence, primary industry is disaggregated while the auto industry, which consumes many finished inputs that may be energy intense, is not. Even though the auto industry is the largest single sector in terms of value-added, it is instead treated as one of the seven sub-components of "Other Manufacturing".

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[18] www.emrg.sfu.ca

A related issue is the degree to which the sub-models cover the costs of producing the given good or service. The price of any good or service is determined by the intersection of supply and demand, but in the long-run it is ultimately determined by the cost of production. For the feedbacks in the hybrid equilibrium model to be comparable to those in a top-down model, it is imperative that it be explicit what costs of production the ISTUM sub-models do and do not cover. The monetary costs in ISTUM capture the purchase cost of physical capital related to the consumption of energy, ongoing labour related to this capital, the energy itself, and any financial surcharges or subsidies. They do not include raw materials or physical or financial capital (and related labour) not related to energy use. Calculations are made throughout to compensate for the missing costs. These calculations generally assume that the uncovered components are unaffected by the changes in the portions covered by the sub-models, except in the case where overall demand is adjusted. These calculations are described with their relevant sections.

3.2 The method used to construct the hybrid equilibrium model CIMS

CIMS estimates the effect of a policy by providing a comparison between a business-as-usual (BAU) market equilibrium and one generated by application of a policy. The dynamics employed in arriving at a new equilibrium are communicated by the physical flows of services and goods produced, as well as by prices for these goods and services, which in turn affect their demand. Which dynamics warranted inclusion, and how they were to be treated, were key questions in the model's design and construction.

Given the structure of the ISTUM sub-models, and a review of the structure of existing general equilibrium models such as CASGEM, I chose to implement a two tiered system of dynamics, one to equilibrate energy supply and demand, and another to equilibrate goods and services supply and demand.[19]

The energy supply and demand integration system adjusts energy prices and quantities by iterative convergence between supply and demand for four energy end-use forms: electricity, natural gas, refined petroleum products and coal. Iterations continue until the change in price falls below a preset threshold.[20] The demand for manufactured products is adjusted using price elasticities that follow the Armington specification, where demand is an empirically calculated mixture of domestic and foreign consumption, while demand for the freight transportation, commercial and residential sectors is adjusted using changes in manufacturing value-added to reflect the indirect structural change effects on disposable income. Personal transportation's demand is adjusted using a mobility demand elasticity.

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[19] Several software environments have been used to run CIMS. ISTUM was originally written in APL (Advanced Programming Language), and the CIMS prototype was built in the same, using a combination of LOTUS and Microsoft EXCEL for data input and output. The key difficulties with the prototype CIMS were associated with the unfriendliness of the interface, and this prototype CIMS was rebuilt with a friendlier interface in a combination of APL, EXCEL / ACCESS, VISUAL BASIC and C++. The use of multiple programming languages, which resulted from different stages being built at different times, lead to difficulties with bugs. A third version is currently being developed, whose engine is still APL but all other interface and data storage functions are in JAVA.

[20] Please see Appendix D for details of the convergence algorithm.

The prices for all goods and services, including energy, are adjusted using multipliers of their base case levels. These are calculated by dividing the current financial life-cycle-cost per unit by that for the previous iteration, including an adjustment for the sub-models' coverage of the cost of production (Equation 6).

$$Multiplier = (FLCC_t / FLCC_{t-1})COP + (1 - COP) \tag{6}$$

$FLCC_t$ = Current financial life-cycle cost for a product
$FLCC_{t-1}$ = Previous financial life-cycle cost for a product from last iteration
COP = Cost of production covered by the sub-model, as a % of total
$Multiplier$ = Corrected price multiplier for a product

Versions of this formula are used throughout the model. The first term explains the portion of costs covered by the CIMS model and how they vary with policy, while the second term represents the portion of costs not represented by CIMS and that does not adjust under the influence of policy. Of key importance is the *COP* parameter, or the percent of the cost of production or service covered by the ISTUM sub-models. The values in the Table 6 are estimates of the percentage of total costs covered by the sub-models. Where possible, they are calculated from Statistics Canada publications.[21]

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[21] "Manufacturing Industries of Canada: National and Provincial Areas, 31-203-XPB" (STC 2002b) and "Financial and taxation statistics for enterprises, 2000 61-219" (STC 2002a).

Table 6 Percentage of the total cost of production / service covered the sector sub-models

Sector		Source
Transportation	95%	Estimate based on the logic that most of transportations cost of service is rolling stock, which is covered by the sub-model. Related infrastructure costs are not normally included in the price of transportation, and therefore have no bearing on its demand. There is low uncertainty associated with this value.
Commercial / Institutional	25%	Estimate based on calculations that relate the capital cost of building shells and equipment that uses energy (HVAC, plug load, appliances) with energy load to the capital value of what goes into the building. There is moderate uncertainty with this value.
Residential	50%	See above.
Mining	55%	Directly calculated value from Statistics Canada publications and values.
Iron & Steel	47%	"
Pulp & Paper	37%	"
Other Manufacturing	15%	"
Chemicals & Plastics	37%	"
Metal Smelting	40%	"
Industrial Minerals	38%	"
Coal Mining	77%	"
Petroleum Refining	8%	Mixture of calculations from Statistics Canada publications, industry calculations and reports on royalty costs.
Crude Extraction	50%	See above.
NG Extraction & Trans.	50%	See above.
Electricity Production	90%	Estimate based on the logic that most of the cost of producing electricity is in the physical capital and plant that produces and distributes the electricity, which is covered by the sub-model.

There are low levels of cost coverage in Commercial/Institutional, Other Manufacturing, and Petroleum Refining. The sub-model covers only the building shells and equipment that use energy in the Commercial/Institutional sector, not the activities that go on in the shells. For Other Manufacturing, it covers only the energy-using auxiliary equipment (pumps, conveyors, compressors), building shells, boilers and electric motors. For example, in an auto manufacturing plant manned by robots only the conveyors that run the assembly line, the pumps that apply the paint and the electric motors that provide drive would be counted. Finally, in Petroleum Refining, a very large portion of the cost of refined product is cost of crude oil input, including royalties and taxes, none of which is covered by the sub-models.

The costing adjustment used above assumes that the relative portion of the cost of production covered by the CIMS sub-models will remain constant under all scenarios and policy regimes. This is not necessarily so, and future work could endogenize more of the currently uncovered costs, especially in the Other Manufacturing sector, which provides a lot of value-added but consumes little energy on a per-unit-GDP basis.

3.2.1 Energy supply and demand feedbacks

In CIMS' energy supply and demand integration system the demands of transportation, industry, residences, and the commercial & institutional sector directly drive the activities of electricity production, refining, coal mining and natural gas and crude oil extraction. Inter-regional transfers as well as net exports are added, as demand for Canada's energy supply sector includes US demand. The importance of domestic demand varies by energy commodity. Most electricity is produced for Canadian consumers, more than half of natural gas produced is shipped to the US, and there is a heavy trade in crude oil and refined petroleum products. Half our domestic crude oil production is shipped to the US, while we import from both OPEC and non-OPEC suppliers.

The energy markets are as follows, with the option of fixed or dynamic pricing as described for each:

- *Seven regional electricity markets*, each with endogenous internal pricing based on the cost of production. The amount of electricity produced is the sum of endogenous domestic demand and net extra-regional exports, which may be adjusted with using an export own-price elasticity.
- *One national natural gas market*, with dynamic pricing using a supply curve based on a combination of Canadian and US market effects. The amount of gas produced is the sum of endogenous domestic demand and net exports. Net exports may be adjusted to reflect changes in the domestic cost of production using an export own-price elasticity.
- *One national crude oil market*, based on an exogenously specified world price of crude oil. The amount of crude oil produced is the sum of endogenous domestic demand and net exports. Net exports may be adjusted to reflect changes in the domestic cost of production using an export elasticity. The world crude oil price is assumed to be unresponsive to Canadian demand.
- *Six refining regions* divide their production amongst seven regions and net exports. All six can use endogenous internal pricing based on the cost of production. The amount of refined petroleum products produced is the sum of domestic regional demand and net extra-regional exports.
- *Four coal producing regions* divide their thermal coal production amongst endogenous domestic regional demand and exogenous exports (i.e. BC is 100% export while Alberta is about 30% export). Due to the high variance in how each non-producing region and sector gets its coal, these regions are assumed to buy coal at a fixed market price or according to a local

supply curve - for example, some electricity plants in Alberta and Saskatchewan are sited at coalfields and are the sole customers.[22]

CIMS divides energy flow in the economy into demand for energy end-use services, intermediate processing, and primary supply (Figure 7). It begins with an initial demand for four general *end-use* energy commodities: electricity, natural gas, coal, and refined petroleum products. The electricity needs of the domestic end-use demand models (transportation, residential, commercial and industry) plus net electricity transfers (inter-regional transfers and exports) are used to drive electricity generation. The refined petroleum products sector is then driven by the net demand from the final demand models, electricity, inter-regional transfers, and net exports. The primary energy supply models, crude extraction, coal mining and natural gas extraction and transmission are then driven by the net demand for their products from the final demand sectors, electricity and refined petroleum.

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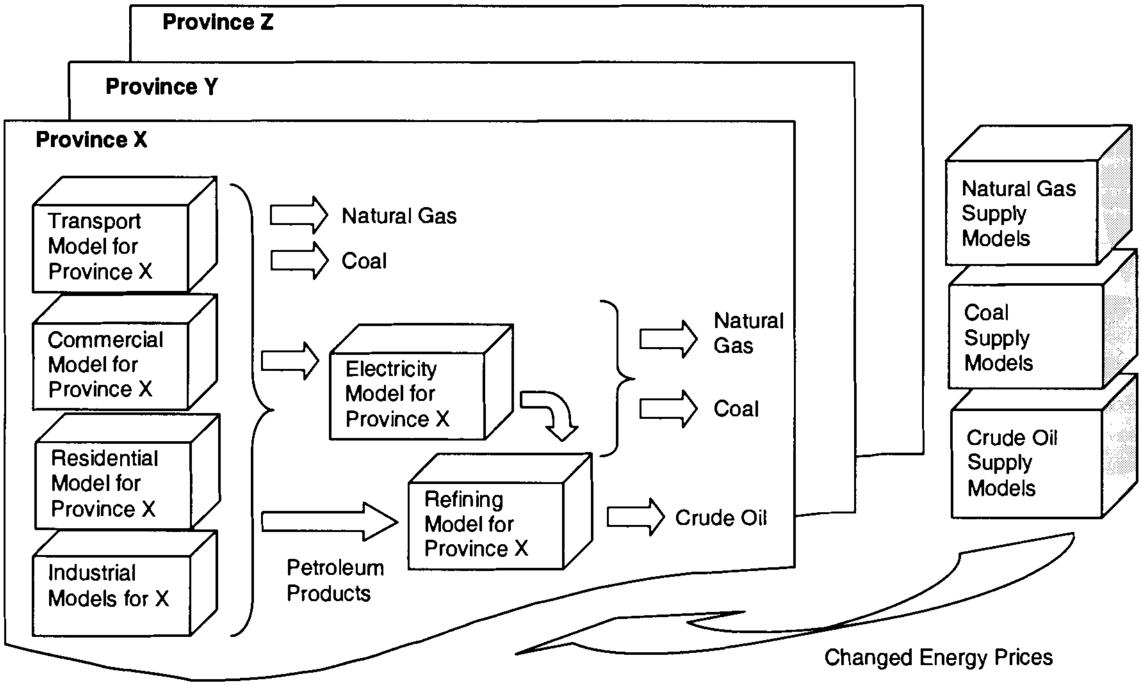
[22] British Columbia, Alberta, Saskatchewan and the Atlantic provinces

Figure 7 CIMS energy supply and demand flow model



The demand for electricity by petroleum refining and the primary energy supply models, for refined petroleum products by the primary energy supply models, and for primary energy supply by the other primary energy supply models, would ideally all be endogenous to the system. However, this would have required yet another set of feedback loops for each of electricity, refined petroleum products, natural gas, and coal and crude oil production. The effect of each of these potential loops was tested manually and they did not have a significant impact on the net effects of either a large GHG tax or change in energy price. It was decided at the time of initial design not to include these loops in the interest of modelling simplicity. The most important interchanges not included in the current version of CIMS as a result of this decision are the potential for self- or co-cogeneration of electricity in the energy supply sectors other than electricity, and natural gas transmission's potential use of electricity for pumping. A system of interior loops, or one that solves the demand for electricity, natural gas, crude oil products and coal simultaneously, may be added to CIMS in the future.

While the price of crude is assumed to be unresponsive to Canadian demand, and coal and NG are priced according to supply curves, electricity and the refining cost of petroleum products may be priced endogenously. This is because they are traded goods whose prices may be largely accounted for by the domestic cost of production. I looked at methods for both average and marginal cost pricing, and decided to follow the usual method used in CGE models, in which constant returns to scale is assumed and average and marginal costs are therefore equal. The intuitive explanation is that if all firms have access to the same technology and markets are competitive then the long-run price is basically equal to the minimum of the long-run average cost curve (Nicholson 1992). The argument for assuming average cost is equal to marginal cost loses force when:

- One is in the short-run where supply is restricted.
- Constant returns to scale do not apply (i.e. the industry is beginning or ending, or supply is restricted for non-cost reasons).
- The cost characteristics of the capital stock are changing, i.e. a new technology is transforming the industry, such as the uptake of combined cycle natural gas turbines in electricity production.

While the last point is a serious consideration for modelling of the Canadian electricity production industry, it is somewhat mitigated by the continuing practice of average cost pricing through monopoly regulation. The ongoing drive to electricity market de-regulation may change this condition in the future.

Canada shares very significant energy trade volumes with the United States and to a lesser extent with both OPEC and non-OPEC suppliers. Canada's biggest energy trade volumes in 2000 (STC 2001) were as follows:

- Exports of natural gas from British Columbia, Alberta and Saskatchewan to the United States = 3627 petajoules (PJ)
- Exports of crude oil from BC, AB and Saskatchewan, mainly to the US = 2851 PJ
- Imports of crude oil to eastern Canada from various suppliers, as well as some refined products (mainly US) = 2257 PJ
- Other exports (coal 192 PJ, natural gas liquids 405 PJ, electricity 125 PJ, other 722 PJ) = 2013 PJ, and other imports (various, not including crude or refined products) = 765 PJ

Given the possible effect of energy policy on the price of producing these commodities, and hence their marketability to the US, electricity, crude oil and natural gas export feedbacks are included in CIMS using price elasticities calculated for the Canadian Federal Department of Finance (Table 7).

Table 7 Price elasticities for energy exports, Wirjanto (1999)[23]

Energy Commodity	Long-run own-price elasticity for export demand
Electric power	-0.54
Natural gas	-0.67
Coal	-0.51
Gasoline and fuel oil	-0.92
Other petroleum products	-0.82

These elasticities follow the Armington specification, whereby the demand for an imported good rises as its price falls relative to the price of its domestic substitute. At all times, consumers buy at least some of the domestic good and some of the imported good, even when the price difference is large (Iorwerth *et al.* 2000, Wirjanto 1999).[24] Implicit in this is the idea the goods produced by

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[23] These values are "dollar" (as opposed to "physical") elasticities, and are half the source values. I considered converting them to physical values (-1) to match CIMS' drivers, but I was uncomfortable with the strength of the weaker "dollar" response as it was. The source values represent the point responsiveness of the long run response to BAU prices. I "damped" this responsiveness so that it would be plausible under a wider range of shocks. In effect, I have kept the relative component of the elasticities, and adjusted the magnitude component.

[24] The main dynamic of the estimation model is paraphrased as follows; "Products, which are goods produced by different countries, are assumed to be imperfect substitutes. The import demand for a product is determined in a separable two-step budgeting process. In the first step the consumer determines her demand for the family of goods to which a product belongs on the basis of her income, the good's price, and the prices of other goods. In the second step she determines her demand for that product on the basis of her total demand for that good given from the first step and of the ratio of the product's price to some weighted average of the prices of other products in that same goods category." The version of CIMS used for this dissertation is for Canada only; therefore, the prices of all foreign products are fixed and the model effectively reduces to an estimate of a price elasticity of a good, modified for that product's share of consumption of its good class and its substitutability for other goods. In effect, I have postulated that at the margin consumers (domestic and foreign), starting from an initial preferred market share for Canadian and foreign goods, respond to increases in the cost of producing of Canadian goods, and hence prices, by transferring their demand for these goods to a foreign substitute according to Equations 8 and 9. The estimating equation that relates the prices and volumes of foreign and domestic market share is as follows (see Wirjanto (1999) for the following equations):

For *i* commodities in time period *t*

$$\log\left[\frac{M_{it}}{Q_{it}}\right] = \alpha_{0i} + \alpha_{1it} + \beta_i \log\left[\frac{PI_{it}}{PP_{it}}\right] + u_{it} \tag{8}$$

where the direct elasticity of demand for M_{it} is calculated using Armington's (1969) formula as

$$\sigma_i = -[\beta_i - S_i(\beta_i - \eta_i)] \tag{9}$$

different countries are not completely substitutable. The energy trade elasticities are applied using Equation 7, which in effect applies the elasticity of the ratio of import volumes to domestic production in relation to a change in the relative price of imports to domestic prices.

$$Adjprod = IT\sigma(((FLCC_t / FLCC_{t-1})COP + (1 - COP)) - 1) \tag{7}$$

$FLCC_t$ = Current financial life-cycle cost for producing the energy commodity
$FLCC_{t-1}$ = Previous financial life-cycle cost for producing the energy commodity
COP = Cost of production covered by the energy producing sub-model, as a % of total cost
σ = Price demand elasticity for the energy commodity
IT= Initial Trade volume of the energy commodity
Adjprod = Additive adjustment to production of the energy commodity

Western Canadian exports of crude oil are physically separated from eastern Canadian imports, as there are currently no large cross-country shipments. While electricity trade is currently a very small portion of our energy trade, electricity import substitution elasticities are included to cover the possibility of a policy driven increase or decrease in electricity exports to the US. All these elasticities operate on the business-as-usual (BAU) export amounts. These elasticities can be single values or they may change over time as specified by the operator of the model.

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where M_{it} are imports of commodity *i*, Q_{it} are sales of commodity *i* by domestic producers, α_{0i} is the estimated intercept of the equation, $\alpha_{1i}t$ is the time trend, β_i is the estimated coefficient that relates the ratio of import and domestic production volumes to their prices (PI_{it} & PP_{it}) (effectively an estimate of the substitutability of imports and domestic goods), *u* is an error term, S_i is the nominal import share of commodity *i* and η is the own price elasticity of demand for good *i*, which Wirjanto assumed to be (-)1. Another way to think of this relationship is that if one replaces Q_{it} with real consumption (expenditure) of good *i* (C_{it}), then β_i becomes a direct measurement of the price elasticity without the Armington formula.

3.2.2 Goods and services demand feedbacks

The economy is commonly divided into *households,* who provide labour and financial capital and consume goods and services, *firms,* who consume capital and labour and provide goods and services, *government,* which consumes goods and services, provides public goods and regulates the market, and finally *foreign producers and consumers* of goods, services and capital (Dornbusch *et al.* 1989). It is common to assume that Canada is a price taker for capital (i.e., the interest rate is set at the world price of capital).

> Canada is assumed to be a small open economy . . . The world interest rate is assumed to be the US prime rate, and foreign savings are assumed to be available elastically. This means that the foreign sector automatically clears any surplus or deficit in the domestic savings market each period, so the domestic interest rate is effectively exogenous. (McKitrick 1998) p.552

I maintained the same assumption as McKitrick, that capital is infinitely available at the world market price. This left me with the circular flow of goods and services between producers (domestic and foreign firms and government, through "public goods" provided via hospitals, schools, and other institutional buildings) and consumers (households, government, and domestic and foreign firms).[25] ISTUM is a model of the physical production side of the economy – the demand side of the economy is mostly missing.[26] To complete the circle

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[25] The terms "public goods" is used loosely here; the technical definition is those goods which will be underprovided by the market due to the lack of excludability. A less than economically efficient amount of public goods will be produced by private producers because the lack of excludability will prevent them from getting a "normal" price, which would be the cost of production plus normal profit given the risks of the endeavour, given the amount demanded.

[26] The one exception is mode choice in transportation, between single occupancy vehicles (people driving alone), high occupancy vehicles (car-pooling), transit and walking/cycling.

between producers and consumers, I needed to add demand feedbacks to the system.

The following suite of options face the consumer or producer when the price of a good or input rises, modelled after the consumer's utility map in CASGEM (Iorwerth *et al.* 2000):

- Substitute an import.
- Buy something else.
- Substitute current consumption for savings.
- Work less and enjoy more leisure, which is the same as reducing output.

These options were used as the primary guide for adding demand feedbacks to the ISTUM sub-models in the construction of CIMS.

Demand feedbacks for manufactured products

Most Canadian industrial products are highly traded; their sensitivity to foreign competition is of prime importance. To reflect this I employ the same Armington specification for price elasticities as used for energy trade, whereby the demand for a foreign good rises as its price falls relative to the price of a domestically produced substitute and consumers always buy at least some of the domestic good and some of the imported good. The price elasticities are applied with the general formula in Equation 10.

$$Multiplier = 1 - (\sigma(((FLCC_t / FLCC_{t-1})COP + (1 - COP)) - 1) \tag{10}$$

$FLCC_t$ = Current financial life-cycle cost for the product
$FLCC_{t-1}$ = Previous financial life-cycle cost for the product
COP = Cost of production covered by the sub-model that produces the product, as a % of total cost
σ = Price demand elasticity for the product
Multiplier = Value by which demand for the product is multiplied

To accommodate the differences between products in the industry sub-models, especially Industrial Minerals, Other Manufacturing, Chemical Products, and Metal Smelting, demand feedbacks are applied to these models at the level where production for individual products is determined. Table 8 provides the elasticities used for sectors and their products. See Appendix E for a full breakdown of the source values and how they were mapped to CIMS' sub-models and their sub-products.

Table 8 Price elasticities used from Wirjanto (1999)[27]

Sub-sectors and their divisions	Value used	Sub-sectors and their divisions	Value used
Metal Smelting		**Chemical products**	
Lead	-0.59	Chlor-alkali	-0.44
Zinc	-0.59	Sodium Chlorate	-0.44
Copper	-0.57	Hydrogen Peroxide	-0.44
Aluminium	-0.59	Ammonia Methanol	-0.44
Nickel	-0.59	Polymers	-0.83
Other manufacturing		**Industrial Minerals**	
Food, tobacco, beverage	-0.32	Cement	-1.75
Rubber and plastics product	-1.30	Lime	-0.53
Leather, textile, clothing	-0.86	Glass	-0.53
Wood products	-0.86	Bricks	-0.53
Furniture, printing, machinery	-0.74		
Transportation equipment	-1.06	**Mining**	
Electrical and electronic equip.	-0.81	Open pit, underground	-1.38
		Potash	-0.58
Pulp and Paper			
Pulp export	-1.72	**Iron and Steel**	
Coated	-0.79	Slabs, blooms, billets &molten steel	-0.6
Uncoated, linerboard, tissue & newsprint	-1.54		

Demand feedbacks for commercial and residential

There is no import substitution for non-traded goods and services such as residential and commercial floor space. Assuming that their income remains constant under a policy, consumers of non-traded goods would buy something else, forego current consumption and save, or simply reduce output (i.e. consume more leisure). If one does not wish to assume a constant income the dynamics become more complicated. In the research leading up to this thesis, I

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[27] These "dollar" elasticities are half their source values. Please see footnote 27 on page 73 and Appendix E for further details.

explored dynamics under both the constant and fluctuating income conditions. The functional responses in CIMS that emerged from these contrasting states are quite different.

For the constant income case, CASGEM, the CGE model used by the Canadian Department of Finance, characterizes the substitution relationship in the following way (Iorwerth *et al.* 2000). Consumers' first step is a choice between current consumption and savings. For current consumption, they will then choose between leisure and goods. Their next choice is between home energy consumption and other goods. They then split their home energy consumption between electricity and fossil fuels. It is at this choice between types of technologies and fuels that the original ISTUM parallels the CASGEM household consumption map. Using CASGEM's substitution pattern in this constant income case for residential, if the cost of residential home energy rises the residential consumer will perform the following sequential substitutions: 1) from home energy consumption to other goods with a cross price elasticity of 0.5 (if the price of home energy rises 1%, demand for other goods rises 0.5%), 2) from goods to leisure with an elasticity of 0.82, and 3) from current consumption to savings with an elasticity of 1.29. All elasticities are from McKitrick (1997, 1998).

One may use the above values for commercial floor space, or substitute in a demand elasticity of choice – some were provided for pure commercial activities (finance, real estate services, etc.) in Wirjanto (1999). Choosing an elasticity was difficult because the ISTUM commercial model comprises hospitals, schools, and government buildings as well as retail and office space. It is the ambiguity of this method that led me to look for a new method, hence the “fluctuating income” or “value-added” method, outlined below.

The consumption for savings and work for leisure substitution method, while reasonable for residential floor space demand, was not completely satisfying for several reasons. First, commercial and residential activity (the amount of floorspace in use) are logically dependent on activity in the manufacturing, industrial and energy supply sectors, be it through secondary economic activity or directly through labour income. Second, the substitution method covers only two of many possible dynamics that may occur as a result of an energy or emissions policy. Many different options were explored, and in the end the most satisfactory was to derive a simple log linear econometric relationship between manufacturing activity, measured as the value of shipments, and residential and commercial activity, measured by value of building permits. This relationship was then used to allow changes in manufacturing value-added to adjust commercial and residential activity (Equation 11).

$$BP_{c,r} = mIVA + b + e \tag{11}$$

$BP_{c,r}$ = natural log of activity (value of building permits) in the commercial or residential sectors in a given year
IVA = natural log of industrial value-added in a given year
e = error term
m = coefficient of relationship (elasticity)
b = intercept

This equation was estimated, using SHAZAM v.9, by running ordinary least squares regressions between manufacturers’ shipments and residential building permits between 1961 and 1991 and manufacturers’ shipments and commercial, institutional, and governmental building permits between 1961 and 1991. All values were deflated using a standard consumer price index.[28] I tested various permutations of the regressions, including lagging and the use of population and year as an independent variable. Table 9 provides the parameter estimates.

Table 9 Parameter estimates used to provide demand feedbacks for the residential and commercial/institutional sectors

Relationship	Adjusted R^2	Independent variable	Intercept	Dependent variable	Notes
Regression between manufacturers' shipments and residential building permits.	0.7473	Manufacturers' shipments ($), m = 1.133, p value = 0.000	b = 2.347, p value = 0.1313	Residential building permits ($)	Year and population were highly collinear and removed from equation.
Regression between manufacturers' shipments and the sum of commercial, institutional, and governmental building permits.	0.6860	Manufacturers' shipments ($), m = 0.7033, p value = 0.000	b = 7.224, p value = 0.000	Commercial, institutional and governmental building permits ($)	Year and population were highly collinear and removed from equation.

The process for calculating manufacturing valued-added, the driver for residential and commercial activity in CIMS, is complex. The sub-model's outputs are designed to capture changes in energy, new capital and labour expenditures engendered by policy. These costs are a sub-component of the total cost of production, which also includes materials and supplies, as well as capital investment, labour and repairs not related to energy using equipment.

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[28] Statistics Canada CANSIM II Data Base: Series V508773, Table Title: Selected Economic Indicators, Series Title: Canada, Manufacturing Shipments 1961-91, Series V4662, Table Title: Building Permits, Values by Activity Sector, Series Title: Dollars, Canada, Unadjusted, Residential 1948M1-2001M3, Series V4665 and V4666, Table Title: Building Permits, Values by Activity Sector, Series Title: Dollars, Canada, Unadjusted, Commercial (V4665) and Institutional and Governmental (V4666) 1948M1-2001M3, Series V508767, Table Title: Selected Economic Indicators, Series Title: Canada, Consumer Price Index 1961-1991

Value-added is defined as the total value of shipments and other revenue, minus the cost of intermediate inputs (energy, materials, and supplies) (Lipsey *et al.* 1998, p.175). Returns to capital include both amortization and profits. Using values for wages, energy expenditures, costs of material, total value of shipments and capital expenditures from Statistics Canada, I found that while the ISTUM sub-models do not capture expenditures for materials or capital unrelated to energy consumption, they capture most capital expenditures in the sectors for which sub-models exist.[29] Supplemental to this, the demand feedback function of CIMS, when faced with a reduction in demand, removes first new growth, then the necessity for replacing retired technology stock, and finally useful stock that is no longer required. Given that most sectors in CIMS grow in most time periods, a simplifying assumption was made that all the productive investment being removed was new or replacement investment, not useful stock. I then compared CIMS' new investment in 2000 with figures from Statistics Canada, and derived a set of multipliers to scale up CIMS' investment figures to reflect the ratio of coverage (the multipliers affect the demand for all stock, not just the portion of the cost of production covered by ISTUM). Finally, I added normal profits as a percentage of revenue, having ascertained that normal profits are included in value-added and that these are not normally included in CIMS.

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[29] "Manufacturing Industries of Canada: National and Provincial Areas, 31-203-XPB" 1989-1990 (STC 2002b) & "Private and Public Investment in Canada, Intentions 2002" (STC 2002c)

These were calculated as a percentage of total costs from Statistics Canada's "Financial and taxation statistics for enterprises, 2000, 61-219".[30]

Demand feedbacks for freight transportation

Freight transportation is important for energy and emissions policy because of the large amount of energy consumed and the amount of GHGs and criteria air contaminants produced.[31] Activity in this sector is directly related to the amount of activity in the rest of the economy. To provide feedback relating freight and economic activity, a similar relationship to that established between manufacturing value-added and residential and commercial activity was incorporated into CIMS. It proved difficult to find an equivalent statistic for freight activity to manufacturing activity as used for the commercial and residential sectors, so instead of an estimated relationship a rule-of-thumb value was temporarily used instead (0.95 – a 1% fall in manufacturing value-added causes a 0.95% fall in freight activity). This relationship allows changes in manufacturing value-added to adjust freight transportation activity. This relationship will be estimated once statistics are available.

Demand feedbacks for personal transportation

Demand feedbacks for personal transportation operate in a similar fashion to the demand feedbacks for manufacturing and industry, except that in the place of an

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[30] Operating profit margin by industries, 1997-1999, p.31.

[31] There are seven air pollutants that are considered Criteria Air Contaminants (CAC). The seven contaminants are Total Particulate Matter, Particulate Matter with a diameter less than 10 microns, Particulate Matter with a diameter less than 2.5 microns, Carbon Monoxide, Nitrogen Oxide, Sulphur Dioxide, and Volatile Organic Compounds. (Environment-Canada 2004)

Armington price elasticity an elasticity for personal kilometers traveled (pkt) in response to the cost of travel is used instead (-0.02) (Michaelis and Davidson 1996). Transportation is also a bit different from the other sub-models in that some demand adjustments occur within the sub-models, specifically the choice between urban modes of transport (single occupancy vehicles, high occupancy vehicles, transit and walking and cycling). The upshot is that much of the structural change possible in transportation is directly included in the sub-sector models.

Limits to the demand adjustments

Experimentation with early versions of CIMS showed that the demand adjustments had to be regarded critically. Elasticities are by nature log-linear measurements, while demand responses are very often non-linear. It may be hypothesized that that there will always be a demand for some commodities, no matter the price. A function for limiting their effects was installed; 50% was chosen as the maximum demand reduction as a rule-of-thumb for the maximum extent to which CIMS' substitution elasticities were still applicable. This demand limiting adjustment is somewhat simplistic, and in the future some form of function that applies limits to demand adjustments in a progressive way will be installed.

3.3 Policy costing & outputs

3.3.1 Policy costing methods associated with ISTUM and early versions of CIMS

Much of CIMS' development was guided by issues associated with deriving costs from its outputs. The cost methodologies in the following sections are described in brief and outline some of the issues in estimating costs.

The ISTUM model was initially designed for energy policy analysis, mainly for assessing how fuel consumption and emissions would change with a given energy policy. The emphasis was on marginal costs, not total or absolute expenditures. The first consistent costing concept was the techno-economic cost, or TEC.

Techno-economic Cost (TEC)

TEC is the difference in estimated (*ex-ante*) financial expenditure on capital, labour, and energy between the Business-as-Usual and Policy cases. It does not *usually* (unless otherwise specified) contain carbon taxes as these are considered a transfer internal to society. It is possible to get negative TEC costs, or benefits, especially in transportation, implying that some actions induced by policy may be profitable.[32] TEC for transportation is often reported according to whether or not to include the capital purchase costs of single occupancy vehicles that are used less because of mode switching to car-pooling or transit, but are

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[32] One of the common effects of energy policy that increases the cost of emissions and fuel is to induce people to drive smaller cars and use transit. Both these movements have direct financial benefits; they cost less than less efficient cars. As these same people seemed to prefer bigger cars and to drive, however, economists commonly assume that they experience a personal welfare loss. Issues like this are at the core of the top-down bottom-up debate over whether energy efficiency and climate reductions are expensive or cheap.

still owned by the operator. This split reflects the challenging question about how vehicle acquisition will be affected by policies to reduce vehicle use. TEC for all consuming sectors are reported with and without electricity price increases, which are sub-regional transfers that balance out to zero at the regional level once the financial effects on electricity producers' revenues are included.

I integrated the ISTUM sub-models under the energy demand and price feedback system in the mid-1999 to 2000 period, thus creating the first version of CIMS. During this period, the model was used for a series of large GHG abatement analyses for Canada. The thrust of these analyses was to integrate and assess a series of emissions reduction actions proposed by panels of interested parties, the Issue Tables of Canada's Climate Change National Assessment Process. Which were the most effective actions with the least costs? CIMS is designed to model real world behaviour, and the most effective and cheapest actions are determined by their welfare costs, as opposed to pure financial costs. This led to the development of the Perceived Private Cost methodology (Bataille *et al.* 2002, Laurin *et al.* 2003, MKJA/EMRG 2000).

Perceived Private Cost (PPC)

PPC is calculated as the GHG tax multiplied by the marginal amount of GHG reductions that occurred at each GHG tax level. The area under the resulting GHG abatement cost curve represents the perceived cost of the actions stimulated by the GHG charge. Negative PPC is not possible. The PPC methodology estimates welfare losses that represent in part the unwillingness of all consumers to switch to technologies that reduce emissions. This fostered development of the Expected Resource Cost methodology, which attempts to more realistically depict the costs and risks associated with a given GHG reduction policy.

Expected Resource Cost (ERC)

ERC was the central concept used to report costs for various analyses done with early versions of CIMS (Bataille *et al.* 2002, Laurin *et al.* 2003, MKJA/EMRG 2000). ERC is equal to TEC+(PPC-TEC)*0.75.[33] The difference between TEC and PPC that is allowed as ERC is a "rule-of-thumb" estimate for what percentage of the difference can be considered real equipment failure risk, as opposed to inefficient resistance to price signals. It represents that perceived cost which *could* turn into real financial cost. Negative ERC is possible, especially at lower GHG charges, but not likely.

Table 10 summarizes the three early costing methods used for CIMS.

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[33] The 25% of the difference between PPC and TEC that is not allocated to ERC is an approximation of the 'inefficient' resistance of the economy to price signals, or what has otherwise been termed a "bribe" necessary to make those who would simply not convert to GHG reducing equipment and processes otherwise. This resistance is built into the inverse power probability distribution surrounding cost estimates of technologies and process in CIMS, and cannot be easily calculated as it represents the area under the long "tail" distribution. Research is underway in this area.

Table 10 Types of costs used in early incarnation of CIMS

Type of cost:	Notes:
Techno-economic costs (TEC) or *"ex-ante financial costs"* Includes change in capital, energy and operations costs (with no uncertainty, no variability and no consumers' surplus).	Most comparable to 'risk-free' financial cost. It can be reported with or without electricity price changes. These electricity price changes result in a transfer to electricity, considered neutral at the regional level.
Perceived private cost. This is based on the concept of private avoided costs; firms and households were willing to reduce X tonnes of GHGs when faced with Y shadow price and all other taxes and real prices in the economy	Established as direct plus indirect emissions reductions times the GHG price.
Expected resource cost (ERC) or *"anticipated ex-post costs"* This may be conceived as the "probable realized" cost or as the perceived private cost adjusted for risk, lost option value and general inefficiency.	ERC = (TEC+(PPC-TEC)*0.75). The missing 0.25 is an estimate of the 'inefficient' resistance of the economy to price signals. ERC is TEC plus the real risk associated with actions.

Distribution of costs under electricity and refining demand changes

Electricity demand changes in all sectors in response to increased electricity prices, leading to an issue of how to distribute GHG reductions as well as TEC and PPC charges. GHG reductions from reduced electricity consumption were accorded to the direct consumer (based on the policy GHG intensity of electricity), who faced increased electricity prices, while electricity producers were accorded the remaining GHG intensity reductions, the TEC costs generated by their intensity reductions plus their changes in revenue. These net transfers, while positive at the sub-regional level, disappear at the regional level.

The relationship between TEC, ERC, option value and welfare costs

The cost difference between ERC and TEC estimated during early analyses was described as risk, or "failure risk", which is related to the concept of option-value

(Pindyck 1991, Dixit 1992, Dixit and Pindyck 1994). Option value is the expected gain from delaying or avoiding an investment while waiting for new information that might lead to a better decision. In consideration of this, ERC may be considered “anticipated ex-post costs”. It may be viewed as the sum of “expected financial costs” (TEC), lost option value, consumers’ surplus losses internal to residential and transportation (internal shifts away from business-as-usual (BAU) preferences within the sub-models) and finally, when demand feedbacks are included, consumers’ surplus losses related to demand adjustments for domestic consumers of domestic goods.[34] It may therefore be considered a measure of personal welfare costs, not including negative environmental externalities (e.g. poorer quality air) or positive public goods (e.g. education, defence or public parks).[35]

3.3.2 Policy costs associated with changes in demand

The inclusion of final demand feedbacks required the addition of five new policy-costing concepts. In all these concepts financial output is defined as a sector’s

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[34] Consumers’ surplus is the difference between a consumer’s willingness to pay and the market price. It ranges from zero for the marginal consumer to large positive values for other consumers.

[35] A key issue in addressing welfare costs concerns the debate over generally sub-optimal pricing in the economy. Much of “basic” economics, based on the assumption of perfect competition, is concerned with maximizing welfare (or achieving Pareto optimality such that none can be made better off without someone becoming worse off) by getting the price of one good or service correct, including the pricing of environmental goods. The “second–best” debate concerns itself with maximizing welfare when some prices, possibly even the majority, are sub-optimal. The four main reasons for this occurring are the presence of imperfect competition, externalities, public goods and distributional considerations (Nicholson 1992). In this second best world it is often argued that maximizing agents will adjust their bargaining or purchasing strategies such that they are suboptimal seen from a view of perfect pricing and competition. In terms of policy Lipsey and Lancaster (1956) made the argument that if all the conditions for a Pareto optimum cannot be satisfied, is not necessarily true that fulfilling some of them is the best policy. The problem must be approached on a case-by-case basis as a problem of constrained optimization.

sales revenue, which includes both value-added and purchased inputs, where value-added is net profits plus the cost of all expenditures on land (unprocessed "gifts of nature"), labour and capital (Lipsey *et al.* 1988).

- The *cost of production effect* on sector financial output. This is equivalent to the increased financial expenditures to adapt to policy, or TEC.
- The *demand effect* on sector financial output. This is equivalent to the reduction in production expenditures associated with lower output.
- The *absolute change* in sector financial output. This is the sum of the cost of production and demand effects.
- *Consumers' surplus losses* associated with demand changes in transportation and residences.
- Changes in *value-added* associated with cost of production and demand changes in manufacturing.

The cost of production and demand effects on sector financial output

The *cost of production effect* captures the internal capital investment and fuel choice adjustments of the model, or the TEC costs endogenous to the model. It is the anticipated financial cost of technical adjustment to the policy. The *demand effect* captures the effects of the demand feedbacks system, or reduction in output, as measured by expenditure compared to the business-as-usual case (BAU). The third is the sum of the first two. These three concepts capture a *portion* of the *anticipated financial cost* of a policy. They do not include the cost of buying emission permits from foreign sources or the cost of imports that replace domestically produced goods for domestic consumption. The fourth item, *consumers' surplus losses*, represents lost consumer welfare associated with reduced residential expenditure and mobility, while the fifth represents the lost *value-added* to manufacturing firms due to policy.

Most GHG policies will increase the cost of production for a given service, increase its price, and thus reduce its demand. This increase in the cost of production will also include the value of carbon charges that are imposed on GHG emissions. These charges are transfers and as such must be subtracted from regional and national costs.[36] Additionally, if demand is inelastic (unresponsive to price) for a given service, the dollar value of the sector, as valued by cost of production, may increase faster than demand reductions, leading to an overall increase in sector value to the economy. If demand is elastic, the opposite may occur.

The standard outputs from the sub-models include BAU and policy values for new physical capital investment associated with consuming energy, labour associated with the latter capital, and energy costs, as well as changes in physical output. It also produces BAU and policy costs per unit output, including GHG charges. These GHG charges are isolated by calculating policy emissions multiplied by the GHG price. When the micro and macro economic dynamics are turned on part of the difference between the BAU and policy cases may be physical output changes, while the rest will be cost of production differences due to internal stock adjustments. CIMS only captures a portion of the price that the

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[36] The question of how to price GHG emissions, be it by tax or by using a capped tradable emission permits system, and how the funds are used are important issues. Key amongst the debates associated with these issues is the hypothetical double-dividend, whereby pollution taxes are used to reduce income taxes, thereby reducing both pollution and increasing the relative attractiveness of labour.

consumer sees; both the BAU and Policy cost per unit are adjusted accordingly. The cost of production and demand effects on sector financial output (SFO) (Equations 12 & 13), and the absolute change in financial expenditure are calculated as follows (Equation 14).

$$\textit{Cost of production effect on SFO} = Q_{Policy}\,(P_{Policy} - P_{BAU} - (Q_{GHG}\,P_{GHG} / Q_{Policy})) \tag{12}$$

$$\textit{Demand effect on SFO} = P_{BAU}\ \ (Q_{Policy} - Q_{BAU}\ ) \tag{13}$$

$$\textit{Absolute change in SFO} = Q_{Policy}\,(\,P_{Policy} - (\,Q_{GHG}\,P_{GHG} / \,Q_{Policy})) - (\,Q_{BAU}\,P_{Policy}) \tag{14}$$

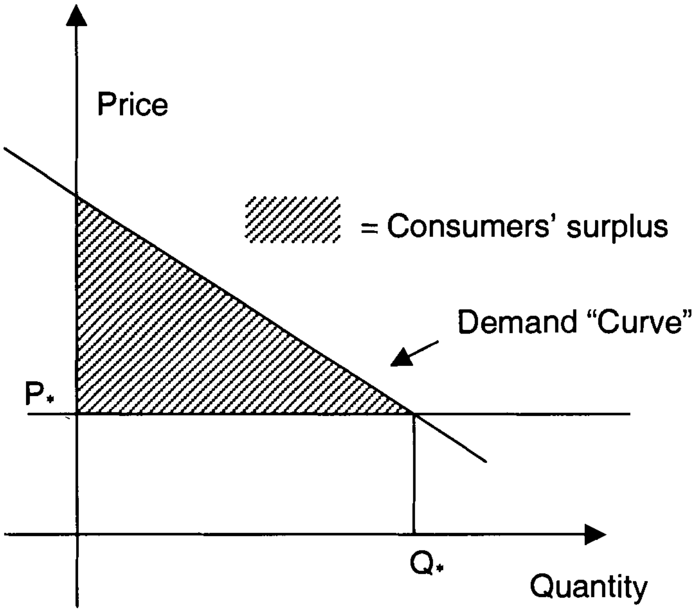
Q_{GHG} = GHG emissions (Tonnes CO_2e)
P_{GHG} = GHG price (\$/Tonne CO_2e)
Q_{Policy} = Policy physical output of good or service X
Q_{BAU} = BAU physical output of good or service X
P_{Policy} = Policy cost per unit of good or service X
P_{BAU} = BAU cost per unit of good or service X

The absolute change in sector financial output could be positive or negative depending on the elasticity of demand – if the cost of production rises faster than demand falls, then the absolute change in financial output could be positive. This results is common with less aggressive policies. The demand effect on sector financial output will always be negative with normal goods, whose demand fall as their price rises. The cost of production effect on sector financial output is usually positive, except for the case where there are decreasing returns to scale.

Consumers' surplus adjustments in residential and transportation

Reductions in residential activity and mobility reflect consumers' surplus losses. Consumers' surplus is the area between the demand curve, which symbolizes the marginal willingness to pay for a service or good, and the market-clearing price of the good or service (Figure 8).[37]

Figure 8 Consumers' surplus diagram



The consumers' surplus loss between BAU and Policy is then calculated as BAU minus the policy. When calculating the direct welfare costs of a policy, consumers' surplus loss is added to the ERC value already calculated. Table 11 summarizes the financial and welfare costs adjustments made to the various sectors when their output changes.

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[37] A reviewer noted that the price may not necessarily be the market clearing price, i.e. the price may be controlled through regulation, etc. For sake of simplicity, these discussions assume simple unregulated markets.

Table 11 **Financial, welfare cost and value-added adjustments induced by changes in output**

	Output adjustment to financial costs	Output adjustment to welfare costs / value-added
Personal Transportation	Demand effect on sector financial value, as measured by expenditure	Difference in **consumers' surplus** under BAU and policy calculated using transportation pkt elasticity
Industry (& Freight Transportation)	Demand effect on sector financial output, as measured by expenditure.	Difference in **value-added** between BAU and Policy.
Residential	Demand effect on sector financial value, as measured by expenditure	Difference in **consumers' surplus** under BAU and policy calculated using combination of savings/consumption and leisure/work elasticities
Commercial	Demand effect on sector financial value, as measured by expenditure	None

The lack of an output adjustment for welfare costs or value-added for the commercial sector is partly due to the nature of the Commercial and Institutional sub-model. It is composed mainly of building shells, HVAC, miscellaneous electricity and air-conditioning systems for government and office buildings, retail space, hospitals, schools, etc. CIMS does not model what these spaces are used for, and thus cannot account for how financial output or value-added may have changed.

3.3.3 Outputs from CIMS

Table 12 provides the outputs specific to the sub-models (i.e., for when they are run by themselves without feedbacks), while Table 13 provides the extra outputs necessary for working with the CIMS' micro and macro economic systems of dynamics (also referred to as feedback systems).

Table 12 Sub-model outputs existing prior to this research

Sub-models	Annualized life cycle costs by sector by year by technology based on behavioural discount rates (20-80%) (See Table 5).
	Fuel use and emissions by sector by year by technology.
	Service and auxiliary use by sector by year by technology.
	Total stock use by sector by year by technology.
	New stock use by sector by year by technology.
	Retrofits by sector by year by technology.
	Technology cost changes due to declining capital cost function

Table 13 Supply and Demand feedback outputs added as a result of this research

Supply and Demand feedbacks	Annualized life cycle cost per unit produced for all sectors by year based on financial cost of capital for both the BAU and Policy case; the model operator sets the cost of capital (e.g. 7.5 or 10%)
	BAU and Policy final demand for each sector's product or service by year.
	BAU and Policy disaggregated energy demand for all sectors by year.
	Changes in disaggregated capital, operations and maintenance, and energy costs by sector by year.
	Changes in GHGs and selected criteria air contaminants (CACs), energy and service use by technology, sorted by technology competition, for BAU and Policy by sector by year.
	Changes in net exports of key energy commodities from BAU to Policy
	Changes in energy prices by year
	Changes in the financial cost of production split into the cost of production and demand effects for industry and manufacturing
	Changes consumers' surplus for personal transportation and residences
	Changes in value-added for industry and manufacturing

3.4 Assessing the characteristics of the hybrid: Measuring AEEI and ESUB

This section outlines how one can generate direct estimates for the ESUB and AEEI parameters for sub-sections and aggregations of the economy using CIMS, and measure the effects of structural change on the parameter estimates.

3.4.1 Calculating the autonomous energy efficiency index (AEEI) using CIMS

Jaccard *et al.* (1998) and Luciuk (1999) provide the basic method for estimating the AEEI. Non-priced induced efficiency occurs mainly through technological advancement, the introduction of new commercially viable processes based on new technologies, and capital turnover. They demonstrate how one may estimate this parameter by comparing two futures in a technology simulation model, one where technological progress is allowed to proceed normally and one where it is frozen at a base case level. Using this method Luciuk simulated an AEEI of 0.69% per year for a subset of ISTUM demand models (Industry, Residential and Commercial) for Canada for the period 2000-2020.

In this study, the method was applied to the whole economy with three different levels of feedbacks: with full demand adjustments, with just energy price and trade feedbacks, and with no feedbacks at all. The rate of AEEI was calculated by comparing a BAU future with one in which there are no technological or process advancements. The BAU future is provided by Natural Resources Canada "Canada's Energy Outlook: An Update" (CEOU) (AMG 2004), the official Canadian government forecast of energy use in Canada used for climate change policy analysis. A special function was added to CIMS that allows the operator to freeze the technology mix at the starting year level, as well as block out retrofitting of existing technology stock with more efficient stock. Energy consumption in the BAU and technologically frozen future is compared, and the difference is annualized using Equation 15, thus producing an annual rate of increase in autonomous efficiency.

$$AEEI=\left[\left(\log\frac{TF}{BAU}\right)\Big/n\right]-1 \tag{15}$$

TF = energy consumption in the (T)echnically (F)rozen universe
BAU = energy consumption in the BAU universe
$AEEI$ = autonomous change in energy efficiency (%/year)
n = number of compounding periods

3.4.2 Calculating elasticities from CIMS

In earlier research, I followed the general method of Griffin (1977) to estimate ESUB parameters from pseudo data, created by simulating a range of input prices in a technologically explicit model (Bataille 1998, Bataille and Jaccard 1998, Jaccard and Bataille 2000). Griffin's method for creating pseudo data involved taking a base case set of independent variables, where there is perfect competition and constant returns to scale, and then multiplying the chosen variables by a matrix of multipliers. In short, Griffin outlines how to "price shock" a model:

> . . . solutions to (1) (the objective function of the linear programming process model Griffin used) are invariant to an arbitrary scaling λ of the price vector p, enabling the derivation of a set of input and output prices (P*) for the pseudo data sample consistent with π = 0 (profits are zero). . . . The effect of the rescaling of output prices is to provide a locus of points where π = 0 and total revenue = total costs (including return to capital)= C (a constant), which defines a price possibility frontier. . . . To achieve a base case solution we multiply a range of known output prices, p_j, by a n X 1 matrix of scalars. (Griffin 1977 pp.390-391)

From the resulting pseudo data, or "future historical data", Griffin estimated Allen partial elasticities of substitution. Table 14 lists the independent and dependent variables in CIMS. The independent variables are candidates for Griffin's price shock method.

Table 14 CIMS' dependent and independent variables

Independent Variables	Dependent Variables
Initial fuel prices	Capital stocks
Technology/capital/process purchase prices	Fuel consumption
Discount rates	Emissions (CO_2, NO_x, CH_4, etc.)
Sector economic growth	Costs
Starting end use demands	End product produced or service provided
Person kilometres travelled or fuel price elasticity	
Armington price elasticities	
Consumption and saving substitution elasticity (Residential and Commercial in Mode One of the macro system)	
Savings versus work substitution elasticity (Residential and Commercial in Mode One of the macro system)	

Given that this research is concerned with the capital for energy and inter-fuel elasticities of substitution, the pseudo data technique was applied to the energy price data. The following multipliers were used to modify the prices for electricity, natural gas, refined petroleum products and coal, individually and one at a time: -50%, -25%, +25%, +50%, +75%. This price range is likely to capture most of the possible variation in the long-term real prices of fuel inputs from 2000 through to 2035, the current simulation period of CIMS. Also, it has been found, after considerable testing, that the -50% to +75% energy price range best captures the range in which the sub-models are most plausible. This limitation is imposed because the sub-models depend on the competition of technologies, which requires a set of known technological options; extreme changes in long-run fuel prices would likely bring new technologies into existence more rapidly. If input price changes were large enough, it could be cost effective to retrofit a wholly new and unknown technology in the place of existing capital stock.

Run Methodology

60 runs of CIMS, each including all the sub-sectors (listed as check marks in Table 15), were necessary to produce the final results (4 fuels X 5 prices per fuel X 3 levels of feedbacks[38] = 60 runs). Each full range of prices (4 fuels X 5 prices = 20 data points) for each sub-sector provided a set of pseudo data outputs for regression. Three regressions, one for each level of feedbacks, were conducted for each of the 84 sub-sector models, for net total of 252 regressions.

Table 15 CIMS sub-sectors for Canada

*Not included in this study due to very small energy use.

Sectors	BC	Alberta	Sask.	Manitoba	Ontario	Québec	Atlantic provs.
Chemical Products	√	√			√	√	
Commerce	√	√	√	√	√	√	√
Industrial Minerals	√	√			√	√	√
Iron and Steel					√	√	
Metal Smelting	√			√	√	√	√
Mining	√		√	√	√	√	√
Other Manufacturing	√	√	√	√	√	√	√
Pulp and Paper	√	√			√	√	√
Residential	√	√	√	√	√	√	√
Transportation	√	√	√	√	√	√	√
Crude Extraction	√	√	√		√		√*
Electricity	√	√	√	√	√	√	√
Coal Mining	√	√	√				√*
Petroleum Refining	√	√	√		√	√	√
NG Extraction	√	√	√	√	√	√*	√

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[38] Full final demand and energy feedbacks, just energy supply and demand feedbacks and no feedbacks

The Econometric Production Function

As was seen in earlier sections, a variety of production functions are commonly used, from those that focus solely on the primary factors (usually just capital and labour) all the way to the (K)apital, (L)abour, (E)nergy, and (M)aterials model (Watkins 1992). In CIMS' sub-models K and E are explicitly modelled in detail, while L is included as a linear percentage of capital employed, depending on the technology. Materials (intermediate inputs other than energy) are not presently included in CIMS, but there are plans to include them in the future.

Capital

The CIMS sub-sector models calculate an annualized capital cost based on revealed implicit discount rates, which are generally quite high (30-80%); see Table 5 and Nyboer (1997). To facilitate regression of the econometric production function, however, it was necessary to calculate the actual annual monetary cost of capital to match against annual fuel costs. This annual cost of capital is based on the opportunity cost of investing in a long-term bond. The purchase value of capital in place is multiplied by an average interest rate (10.0%) to give a value for capital being amortized, or "spent", in the period in question. Capital is therefore defined as the purchase price per unit of physical capital times the number of units, annualized for the period in question.

The sub-sectors models of CIMS simulate the long-run level of capital acquisition and capacity utilization. The capital retrofit, replacement, and purchasing process is simulated once every five years. It is assumed that the capital user will purchase the amount of capital they can keep employed at an optimal level, given all the various factors they have to weigh, including business cycles, maintenance, etc.

Energy

Energy purchases are defined as the amount of energy purchased, in gigajoules, minus the amount that may be produced by the industry, i.e., electricity via self- or co-generation. Fuel prices start at the value forecasted in Natural Resources Canada's "Canada's Energy Outlook-an Update", and may then be modified as the energy price and demand feedbacks are activated in CIMS. In certain key models, such as electricity, the price of natural gas was increased to reflect that forecast prices in "Canada's Energy Outlook – An Update" (CEOU) have been low relative to experience for the last nine years.

Labour

Labour costs in CIMS are currently represented as a percentage of capital costs for individual technologies. It is therefore an *a priori* complement to machinery and buildings, a Leontief complementarity relationship that specifies a fixed ratio of factors. This practice was adopted because within the sub-models production is depicted at the individual technology or process level – there is very little scope for substitution within a single technology or process. The fixed relationship between capital and labour also meant that they could not be regressed together as independent variables, as this would have introduced collinearity.

Input substitution in the sub-models occurs when the technologies are competed. This would suggest that most substitution between capital and labour occurs when firms and households select between goods whose production is more or less labour- or capital- intensive. This substitution occurs at the macro economic modelling level, not at the machine or technological process level.

Equation 16 describes the generalized production function within the sub-models.

$$\text{Output} = f\,(K_{\text{Capital}}, E_{\text{Electricity}}, E_{\text{Natural Gas}}, E_{\text{Oil}}, E_{\text{Coal}}) \tag{16}$$

I chose to use the transcendental logarithmic (translog) production function (Equation 17) to regress the pseudo data because it is a highly general functional form, one that places no *a priori* restrictions on the Allen elasticities of substitution (Berndt and Wood 1975, Nicholson 1992).

$$\ln q = \alpha_0 + \sum_{i=1}^{n} \alpha_1 \ln x_i + 0.5 \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \ln x_i \ln x_j \tag{17}$$

where q is output, the α's and β's are parameters to be estimated, $x_{i...n}$ are the inputs, and bilateral symmetry of substitution between inputs ($\beta_{ij} = \beta_{ji}$) is imposed.

While it is possible to directly estimate all the above parameters, it is more efficient to logarithmically differentiate in the translog and apply Sheppard's Lemma. This produces the following set of cost share equations that can then be directly estimated as a system, with symmetry restrictions ($\beta_{ij} = \beta_{ji}$) (Equation 18).

$$\begin{aligned}
S_{(K)apital} &= \alpha_K + \beta_{KK}\ln(P_K) + \beta_{KE}\ln(P_E) + \beta_{KN}\ln(P_N) + \beta_{KO}\ln(P_C) + \beta_{KC}\ln(P_O) \\
S_{(E)lec} &= \alpha_E + \beta_{KE}\ln(P_K) + \beta_{EE}\ln(P_E) + \beta_{EN}\ln(P_N) + \beta_{EO}\ln(P_C) + \beta_{EC}\ln(P_O) \\
S_{(N)G} &= \alpha_N + \beta_{KN}\ln(P_K) + \beta_{EN}\ln(P_E) + \beta_{NN}\ln(P_N) + \beta_{NO}\ln(P_C) + \beta_{NC}\ln(P_O) \\
S_{(O)il} &= \alpha_O + \beta_{KO}\ln(P_K) + \beta_{EO}\ln(P_E) + \beta_{NO}\ln(P_N) + \beta_{OO}\ln(P_C) + \beta_{OC}\ln(P_O) \\
S_{(C)oal} &= \alpha_C + \beta_{KC}\ln(P_K) + \beta_{EC}\ln(P_E) + \beta_{NC}\ln(P_N) + \beta_{OC}\ln(P_C) + \beta_{CC}\ln(P_O)
\end{aligned} \tag{18}$$

where each of $S_{(K,E,N,O,C)}$ are the input cost shares of each input, each of $P_{(K,E,NO,OC)}$ are the input prices, $\alpha_{(K,E,N,O,C)}$ are base estimated cost shares, and the β's are estimated coefficients that relate the log of the price of capital and each energy type to the cost share of the relevant input.

Following the norm in the literature for comparability, Allen partial elasticities of substitution were calculated for the translog function.[39] Allen partial elasticities represent the input elasticities of substitution adjusted for cost share, and as such allow comparison between inputs with different cost shares. Equation 19 and 20 provide the formulas for the own and cross price elasticities of demand using the cost shares (S_{ij}) and estimated coefficients (β_{ij}). Further details of the econometric model are in Appendix F.

Cross Price Elasticity of Demand

$$\sigma_{ij} = \frac{\beta_{ij} + S_i S_j}{S_i S_j} \qquad i,,j = 1, \ldots, n \text{ but } i \neq j \tag{19}$$

Own-price Elasticity of Demand

$$\sigma_{ii} = \frac{\beta_{ii} + S_i^2 - S_i}{S_i^2} \qquad i = 1, \ldots, n \tag{20}$$

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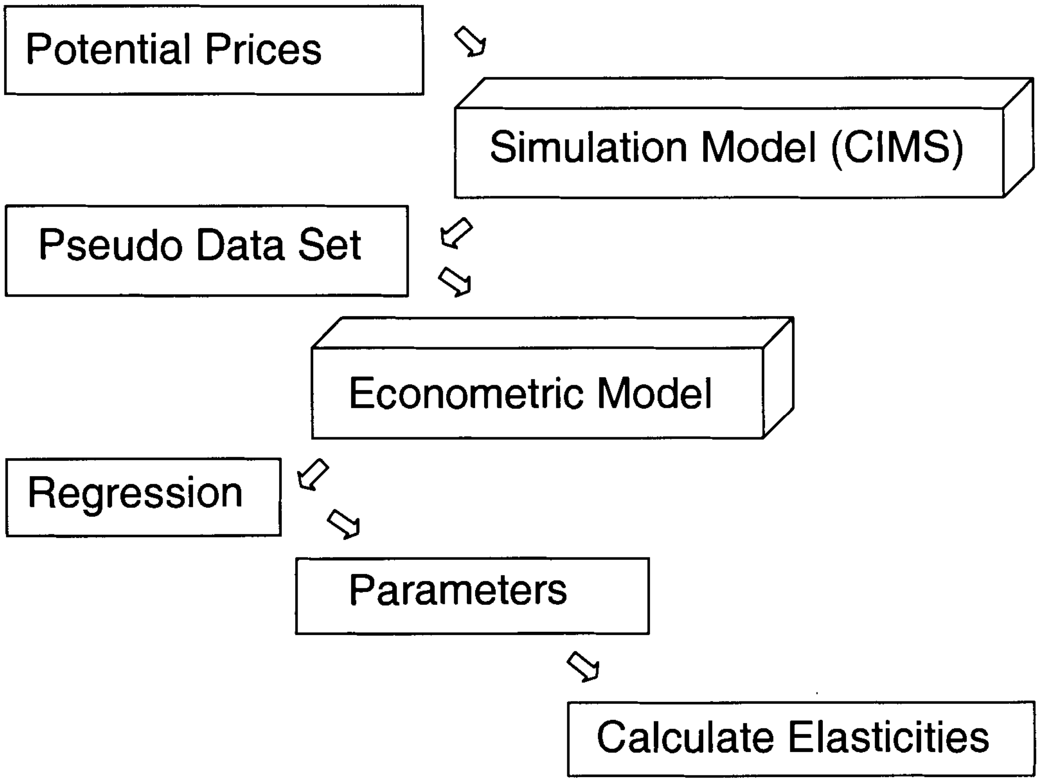
[39] Other choices could have been the Morishima or McFadden formulations. There is a wide and hotly debated literature about which is most appropriate. Allen partial elasticities are the most commonly used, and thus the most comparable.

Finally, the sector elasticities were weighted by cost and aggregated to find the provincial and national substitution elasticities. This aggregation provided parameters comparable to those used by macro models of the economy. Figure 9 is a graphic depiction of the elasticity calculation process.

Figure 9 Graphic depiction of elasticity calculation method



3.5 Using CIMS for policy analysis: Cost curves of GHG abatement in Canada

The purpose of energy policy modelling is to help policy makers decide what to do, i.e. evaluate the cost and effectiveness of alternative policies. The long-term value of CIMS may be measured by how it directly informs policy makers, and more generally, by how it poses new hypotheses and clarifies old ones. During the period in which CIMS was being built the Energy and Materials Research

Group of Simon Fraser University was asked by the Canadian National Climate Change Process, a multi-stakeholder body, and by the Office of Energy Efficiency of Natural Resources Canada, to contribute to three separate climate change costing exercises using CIMS. As the model designer I was heavily involved in analysis and management for all three, and was project manager for Bataille *et al.* (2002). The first was an exercise in integrating emission reductions actions specified by stakeholders into a coherent framework with some energy price feedbacks (MKJA/EMRG 2000). The second was an exercise in which a “cost curve” of national reductions associated with 11 different GHG prices was constructed ($10, $20, $30, $40, $50, $75, $100, $125, $150, $200, $250 / t CO_2e) and the actions that produced these reductions were documented and analyzed. (Bataille *et al.* 2002). The third was a reduced repeat of the latter exercise including updated data and demand feedbacks for $10, $30, $50, $100 and $150 / t CO_2e (Laurin *et al.* 2003). Some results from these projects are provided in the next chapter to demonstrate the abilities and issues associated with doing policy analysis with CIMS. These results are preceded by a simpler version of the cost curves exercise for $10, $25, $50, $100 and $150 / t CO_2e and four states of the world: 1) with no feedbacks, 2) with energy supply and demand feedbacks, and 3) the latter with energy trade feedbacks and finally, 4) full feedbacks. This exercise assesses how using CIMS’ feedback systems changes the results of the sub-models when faced with a given GHG policy. It also allows for estimation of the separate contributions to GHG abatement of technological adjustment and the direct and indirect effects of structural change, thus addressing the questions posed by Loulou and Kanudia (2000). I focus on the GHG emissions reductions for the simpler exercises, and provide a summary of the costing results of the full-scale cost curves exercises.

3.6 Methods & data summary

The preceding chapter laid out the methods and data used to: 1) build the hybrid model CIMS out of the bottom-up model ISTUM, 2) estimate AEEI and ESUB parameter values from CIMS, 3) separate the GHG intensity, direct and indirect effects of structural change and 4) estimate cost curves of GHG abatement from CIMS. Chapter 4 provides the direct results of 2, 3, and 4, while Chapter 5 discusses their implications. Chapter 6 provides future direction.

4 Results

Chapter 4 provides: 1) summaries of the AEEI and ESUB parameter estimations made with CIMS, 2) an estimated separation of the effects of GHG intensity, direct and indirect structural change and 3) costs curves of GHG abatement for Canada. Details of the AEEI and ESUB calculations and the regressions that supply these calculations with parameters are available in Appendix H, a set of compressed CD-ROMs.

4.1 The autonomous energy index (AEEI)

Table 16 summarizes the sectoral AEEI with the three levels of feedbacks, as well as providing a summary for the demand sectors, whose aggregate value is equivalent to that used in macro models. Simulating CIMS with and without technological development, Canada's AEEI for the demand sectors, (equivalent to the AEEI normally used in MACRO, MERGE and the CGE models such as MIT-EPPA) was estimated to be 0.44 %/year including transportation, and 0.66 with it excluded (Table 16). The split is given because of transportation's relatively low AEEI (0.11 %/year) and large share of energy expenditure, which lowers the aggregate values.

None of the sectors, with the possible exceptions of transportation, iron and steel and pulp and paper production, showed much sensitivity to the level of feedbacks employed. Due to this lack of effect, further discussion assumes full feedbacks.

The commercial/institutional sector has by far the highest estimated AEEI (1.70 %/year), mainly due to a suite of potential building shell improvements. The residential sector's estimate of 0.46 %/year is comparable to the standard value suggested by Manne and Richels (1994) and used by MERGE and McKitrick. Industry's values are somewhere in between, with large differences between specific sectors (0.14-0.92 %/year).

Table 16 AEEI results

Sector / Regions		**AEEI % / year**		
		All feedbacks (inc. goods and services demand feedbacks)	**Energy supply and demand feedbacks**	**No feedbacks**
Canada (analogous to that used in macro models) (Demand, w/ & w/o Transport)		0.44 / 0.66	0.41 / 0.65	0.41 / 0.65
Canada (Energy Supply)		-0.62	-0.61	-0.63
Canada (Demand and Energy Supply)		0.08	0.07	0.06
Demand Sectors				
Residences		0.46	0.46	0.46
Commercial & Institutional		1.70	1.70	1.69
Transportation		0.11	0.05	0.05
Industry	Total	0.27	0.26	0.26
	Chemical Products	0.26	0.27	0.27
	Industrial Minerals	0.92	0.92	0.92
	Iron and Steel	0.31	0.23	0.23
	Metal Smelting	0.49	0.47	0.47
	Mining	0.37	0.39	0.39
	Other Manufacturing	0.20	0.19	0.19
	Pulp and Paper	0.14	0.11	0.11
Energy Supply Sectors				
	Crude Oil Extraction	-2.07	-2.07	-2.07
	Electricity	-0.86	-0.84	-0.87
	Coal Mining	0.65	0.65	0.65
	Petroleum Refining	0.39	0.39	0.39
	NG Extraction	0.22	0.22	0.22

Transportation's relatively low AEEI can be explained by behavioural preferences for larger and less efficient equipment (trading economy cars for sport utility vehicles) and for traveling individually in single occupancy vehicles (single occupancy vehicles are preferred to high occupancy vehicles, transit, cycling and walking). It is possible that CIMS' transportation model is too resistant to technical developments in the face of policy, but AEEI for transportation has likely been negative over the last decade, with the shift to light duty trucks and vans (including SUVs), so the low AEEI is quite plausible.

Electricity production and crude extraction have negative AEEI. For electricity, this is partly a definitional issue, explained by the exhaustion of good hydroelectric sites, which technically consume no primary energy (oil, coal or natural gas) to produce electricity, and the allocation of new electricity demand to thermal sources. For crude oil extraction, the negative index may be explained by the exhaustion of easier methods for extracting crude oil, and the resulting move to enhanced oil recovery, deeper wells, and oil sands extraction.

Table 17 compares the AEEI values calculated here with those reported in the surveyed models of Ch.2 and Williams' 1990 survey of bottom-up models (Williams 1990).

Table 17 **Non-priced induced energy efficiency indices**

Model	**Aggregate AEEI (%)**	**Notes**
CIMS National AEEI w/wo transportation	0.44/0.66	Sector variation around this mean is wide
Williams (1990) survey of bottom-up models	1.5-3.0	
SGM	NA	Used for calibration
MS-MRT	NA	Used for calibration
MIT-EPPA – US Note: AEEI for all MIT-EPPA is applied as a logistic; efficiency growth gradually slows over time as producers exhaust the technical potential for saving energy. Primary energy sectors do not experience AEEI.	1.301	Sourced from expert elicitation and reviews of other climate policy work. These values decline with time.
MIT-EPPA - Other OECD	1.210	"
MIT-EPPA – China	1.980	"
MIT-EPPA – India	1.430	"
MIT-EPPA – ROW	1.100	"
G-Cubed	1	
MERGE/Global 2100	0.5	Guesstimated
CETA	0.25	Guesstimated
MARKAL-MACRO (DDF) Residential	0.75	Guesstimated
MARKAL-MACRO (DDF) Commercial	0.5	Guesstimated
MARKAL-MACRO (DDF) Elec. Appl.	0.25	Guesstimated
McKitrick	0.5	Guesstimated, cited as a standard literature value by author

A priori, given their relative treatments of technology and technological "optimism", one might expect the AEEI values for the bottom-up models to be the highest, followed by MARKAL, then CIMS, and finally the macro models. The reality is slightly different. While the bottom-up estimates are the highest (1.5-3.0 %/yr), they are followed by MIT-EPPA (1.301 %/yr for the US), G-Cubed (1.0

%/yr), MARKAL (0.25-0.75 %/yr), MERGE (0.5 %/yr), CIMS' estimates (0.44/0.66 %/yr), and CETA (0.25 %/yr). As a top-down model, MIT-EPPA's deviation from expectation is partially explained by MIT-EPPA's values falling with time, explained in their documentation as a gradual exhaustion of energy efficiency potential. G-Cubed's value seems high, and may be explained by its production function structure or estimated nature of the model, but this is uncertain. MARKAL, MERGE, CIMS, and CETA's values all lie within the *a priori* expectations.

Table 18 and 19 show the change in the cost of production per unit by sector and the resulting change in demand when technology is not allowed to change. For example, with no autonomous energy efficiency improvements, BC Pulp and Paper would experience a 3% per annum increase in cost of production, and a 6% loss in demand. Lower industrial and manufacturing activity leads to lower secondary economic activity in the commercial, residential and freight transportation sectors. Logically, the converse occurs in the energy supply sectors – their demands are all substantially larger.

Table 18 Cost of production with technical change frozen as a percentage of the BAU cost of production (2030)

Sectors	Regions						
	BC	AB	SK	MB	ON	PQ	MT
Demand							
Commercial and Inst.	91%	97%	90%	96%	93%	96%	96%
Residential	89%	88%	89%	94%	91%	93%	96%
Transportation	99%	99%	99%	100%	100%	99%	100%
Chemical Products	99%	100%			106%	97%	
Industrial Minerals	109%	105%			116%	98%	104%
Iron and Steel					111%	109%	
Metal Smelting	119%			203%	112%	104%	98%
Mining	100%		109%	92%	102%	101%	101%
Other Manufacturing	100%	101%	118%	113%	104%	105%	101%
Pulp and Paper	103%	112%			107%	102%	103%
Energy Supply							
Crude Extraction	109%	90%	117%		164%		111%
Electricity	98%	96%	113%	110%	107%	105%	86%
Coal Mining	106%	109%	122%				98%
Petroleum Refining	108%	104%	114%		115%	137%	118%
Natural Gas	100%	100%	102%	104%	103%	103%	101%

Table 19 Demand in the technically frozen universe as a percentage of the business as usual universe when demand for all sectors is adjusted (2030)

Sectors	Regions						
	BC	AB	SK	MB	ON	PQ	MT
Demand							
Commercial and Inst.	94%	97%	90%	94%	91%	93%	96%
Residential	93%	97%	89%	94%	91%	92%	96%
Transportation	96%	98%	95%	97%	96%	96%	97%
Chemical Products	99%	100%			99%	100%	
Industrial Minerals	99%	99%			96%	99%	99%
Iron and Steel					96%	97%	
Metal Smelting	92%			83%	98%	98%	101%
Mining	100%		93%	106%	99%	99%	99%
Other Manufacturing	100%	100%	100%	100%	100%	100%	100%
Pulp and Paper	94%	94%			97%	96%	98%
Energy Supply							
Crude Extraction	120%	102%	106%		110%		108%
Electricity	118%	110%	108%	108%	117%	115%	114%
Coal Mining	100%	147%	152%				144%
Petroleum Refining	146%	103%	107%		107%	103%	108%
Natural Gas	93%	93%	93%	93%	93%	93%	93%

In summary, the calculated AEEI are characterized by the following trends:

- The individual sector estimates differ widely, suggesting structural heterogeneity. Given a policy that stimulates structural change, this heterogeneity may have important implications for the final impact of the policy. Given this, the use of a single AEEI for the whole economy, such as in MACRO, MERGE, CETA and McKitrick's work, may be misleading.
- Most demand sectors (except transportation) and natural gas extraction, coal mining and petroleum refining all have positive AEEI of 0.2 or more, indicating that non-priced induced reductions in energy intensity plays a role in long term energy demand in these sectors.
- According to the parameter values and technology data currently in CIMS, energy intensity is forecast to remain relatively the same for the next 30 years.
- Electricity is forecast to have negative AEEI, which is mainly due to increased growth in thermal electricity compared to hydro. This is partly a matter of definition, as the water used to make electricity does not count as energy consumption.
- Crude oil extraction has a strongly negative AEEI, presumably due to the shift to energy intensive supply activities such as production of synthetic oil from oil sands.

A final point from this experiment was the effect of technical development on overall economic activity. Most technological changes reduce the cost of producing goods, and thus their price. Technical change therefore works to increase consumption over time, and thus overall economic activity. In the technically frozen universe in 2030 annual secondary economic activity is 3% (AB) to 11% (SK) lower compared to the business-as-usual future, as measured by changes in activity in the residential and commercial/institutional sectors. For the primary industries in the table, this translates into annual activity losses of between 4% and 13.5%.

4.2 Elasticities of substitution (ESUB) results

The ESUB estimates are presented with an initial focus on the national and sectoral capital for energy substitution elasticity. Table 20 provides a summary of sectoral estimates with the three levels of feedbacks.[40]

The ESUB for Canada is presented with transportation included (0.13) and excluded (0.27). Thus, a 1% rise in the relative price of energy will lead to a 0.27% rise in the relative demand for capital, with transportation excluded. The residential and commercial / institutional sectors show moderate substitutability, while industry shows low substitutability for most sectors, with large relative differences between them. Transportation's capital for energy substitution elasticity is much lower than the rest of the economy, which implies insensitivity to changes in the costs of energy, at least at the levels simulated. There is some indication that transportation's behavioural parameters may be unrepresentative of a true long term response to price changes, which will be discussed in the next chapter.

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[40] All regressions have coefficients of variation (adjusted R^2) equal to 0.7 or higher, with most being 0.85 and higher. Most of the dependent variables were strongly significant, with p-statistics of 5% or lower, with most being less than 1%. This is to be expected given that, as a cost based model, CIMS will respond to changes in input costs in predictable ways. The detailed tables and calculations of the statistical regressions are included with the hard copy of this thesis compressed onto a CD appendix (Appendix H) and are available on request.

Table 20 Capital for energy substitution elasticity by nation and sector with all feedbacks operating

Sector / Regions		Capital (K) for (E)nergy ESUB		
		All feedbacks (inc. goods and services demand feedbacks)	Energy supply and demand feedbacks	No feedbacks
Canada (w/&w/o Transport)		0.13 / 0.27	0.12 / 0.23	0.12 / 0.25
Demand Sectors				
Residences		0.33	0.30	0.32
Commercial & Institutional		0.24	0.19	0.21
Transportation		0.08	0.08	0.08
Industry	Total	0.11	0.05	0.06
	Chemical Products	0.02	0.00	0.01
	Industrial Minerals	0.32	0.33	0.36
	Iron and Steel	0.11	0.02	0.02
	Metal Smelting	0.02	0.04	0.05
	Mining	0.18	0.14	0.15
	Other Manufacturing	0.01	0.01	0.03
	Pulp and Paper	0.31	0.10	0.10
Energy Supply Sectors				
	Crude Oil Extraction	-0.07	-0.09	-0.07
	Electricity	0.20	0.19	0.18
	Coal Mining	0.39	0.38	0.39
	Petroleum Refining	-0.10	-0.07	-0.10
	NG Extraction	-0.26	-0.29	-0.28

For a policy goal like GHG reduction, elasticities for individual fuels are of particular interest because some are much more GHG-intensive than others. Table 21 shows ESUB values between capital and individual forms of energy for three levels of feedbacks. The lack of changes between the parameter measurements at the different feedback levels seems to indicate that most capital for energy substitutability comes directly from the technology choice level, and is relatively unaffected by structural change.

Table 21 National capital for energy elasticities of substitution

		Canada	Canada w/o Transport
K:Energy	Demand and energy feedbacks	0.13	0.27
	Energy Feedbacks	0.12	0.23
	No feedbacks	0.12	0.25
K:Elec	Demand and energy feedbacks	0.33	0.33
	Energy Feedbacks	0.28	0.28
	No feedbacks	0.28	0.28
K:Oil	Demand and energy feedbacks	0.08	0.04
	Energy Feedbacks	0.08	0.03
	No feedbacks	0.09	0.09
K:NG	Demand and energy feedbacks	-0.05	-0.05
	Energy Feedbacks	-0.10	-0.10
	No feedbacks	-0.05	-0.05
K:Coal	Demand and energy feedbacks	-0.04	-0.04
	Energy Feedbacks	0.21	0.21
	No feedbacks	-0.04	-0.04

The capital for electricity ESUB, which indicates weak to moderate substitutability, is the biggest relative source of energy efficiency. The capital for petroleum products ESUB indicates weak substitutability, mainly due to the low estimated potential for efficiency in transportation. The capital for natural gas and coal ESUBs are both characterized by very weak complementarity, with the exception of the capital for coal ESUB when no demand feedbacks are allowed. This relationship is also the only one that changes significantly between feedback levels, and is a byproduct of electricity being more substitutable for capital than the other fuels at all feedback levels. With no goods and services demand feedbacks, more electricity is demanded and produced at a higher cost to replace the other fuels when their price rises. With inclusion of goods and services demand feedbacks, the extra cost increases prices, which reduces goods and services demand and finally lowers the overall level of electricity demanded.

Overall, Table 21 suggests that a CIMS simulation finds negligible substitution between capital and individual forms of energy. This is as expected given the small partial ESUBs between capital and the energy aggregate. This suggests that the potential for energy efficiency improvements is small – at least given the estimated technology data and behavioural parameters in the CIMS model.

Given the general lack of structural effects on the substitution parameters, Tables 22 and 23 provide ESUB estimates with full feedbacks only. The two exceptions to this general lack of structural effects on the ESUBs are Iron and Steel (K for E σ's = 0.11, 0.02 and 0.02 for full final demand, energy supply and no feedbacks respectively – see Appendix G) and Pulp and Paper production (K for E σ's = 0.31, 0.10 and 0.10) , which have a relatively strong sensitivity to demand feedbacks. This is a combination of their relatively high-energy intensity, moderate ability to substitute capital and energy, and a high import substitution elasticity, or propensity for their final demand to fall in response to price due to both pure demand responses and import substitution.

Table 22 presents the estimated inter-fuel ESUB values. All the own-price elasticity estimates are negative, as expected. Electricity for refined petroleum products (RPP), electricity for natural gas, RPP for natural gas, natural gas for coal and coal for RPP all display a high degree of substitutability. When energy supply and demand feedbacks are allowed there is a tendency to switch to electricity; this trend reverses when goods and services demand feedbacks are included, as the high cost of electricity drives down demand for the end-product good or service. Table 23 summarizes the capital for energy, inter-fuel and own-price elasticities by sector and fuel.

Table 22 **National inter-fuel elasticities of substitution**

		Canada	Canada w/o Transport (only for Oil relationships)
Elec own-price	Demand and energy feedbacks	-1.95	NA
	Energy Feedbacks	-1.79	NA
	No feedbacks	-1.77	NA
Elec:Oil	Demand and energy feedbacks	1.73	1.96
	Energy Feedbacks	1.79	2.23
	No feedbacks	1.70	1.94
Elec:NG	Demand and energy feedbacks	1.91	NA
	Energy Feedbacks	1.91	NA
	No feedbacks	1.91	NA
Elec:Coal[41]	Demand and energy feedbacks	0.01	NA
	Energy Feedbacks	0.42	NA
	No feedbacks	-0.02	NA
Oil own-price	Demand and energy feedbacks	-0.35	-2.74
	Energy Feedbacks	-0.35	-2.84
	No feedbacks	-0.36	-2.85
Oil:NG	Demand and energy feedbacks	1.27	2.25
	Energy Feedbacks	1.27	2.27
	No feedbacks	1.26	2.27
NG own-price	Demand and energy feedbacks	-1.69	NA
	Energy Feedbacks	-1.64	NA
	No feedbacks	-1.70	NA
NG:Coal	Demand and energy feedbacks	0.95	NA
	Energy Feedbacks	0.88	NA
	No feedbacks	0.62	NA
Coal own-price	Demand and energy feedbacks	-1.16	NA
	Energy Feedbacks	-2.15	NA
	No feedbacks	-1.25	NA
Coal:Oil	Demand and energy feedbacks	1.29	NA
	Energy Feedbacks	1.29	NA
	No feedbacks	1.75	NA

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[41] The inter-fuel elasticities of substitution for electricity and coal are highly sensitive to the level of feedbacks. This is due to the aforementioned tendency to substitute electricity and capital when the increased price is not passed to the consumer, thus triggering a fall in demand. When the full cost is passed to the consumer and they are allowed to adjust their demand, this substitution pattern is less evident.

Table 23 **Summary of substitution relationships with demand feedbacks on (K = Capital, En=Energy, E=electricity, N=Natural gas, O=Petroleum Products, C=Coal, (Ep, Np, Op, Cp)=Own-price elasticities**

Region / Sector	**Substitution Relationships (K:EN = Capital for Energy), * = not applicable**														
	K:En	**K:E**	**K:N**	**K:O**	**K:C**	**E:N**	**E:O**	**E:C**	**N:O**	**N:C**	**C:O**	**Ep**	**Np**	**Op**	**Cp**
Canada (Demand, w/ Trans.)	0.13	0.33	-0.05	0.08	-0.04	1.91	1.73	0.01	1.27	0.95	1.29	-1.95	-1.69	-0.35	-1.16
Canada (Demand, w/o Trans.)	0.27	0.33	-0.05	0.04	-0.04	1.91	1.73	0.01	2.25	0.95	1.29	-1.95	-1.69	-2.74	-1.16
Demand															
Commercial and Inst.	0.24	0.21	0.15	0.79	*	2.66	2.11	*	1.60	*	*	-2.31	-3.00	-3.00	*
Residential	0.33	0.61	-0.35	-0.37	*	2.98	2.99	*	2.76	*	*	-2.66	-2.77	-3.00	*
Transportation	0.08	0.16	0.07	0.08	*	-3.00	1.51	*	1.00	*	*	-2.77	-2.68	-0.10	*
Industry															
Chemical Products	0.02	0.05	-0.09	0.39	0.16	0.05	0.77	-0.36	3.00	-2.82	•	-0.35	-1.36	-3.00	-0.67
Industrial Minerals	0.32	-0.18	0.59	0.72	0.68	0.62	1.23	2.69	2.25	2.62	3.00	-0.54	•	-3.00	-3.00
Iron and Steel	0.11	0.16	0.21	0.01	-0.03	0.06	-0.67	3.00	1.69	0.08	-0.23	-1.39	-2.26	-1.80	-0.09
Metal Smelting	0.02	0.01	0.20	-0.54	-0.28	0.25	-0.02	3.00	2.76	1.96	2.22	-0.13	-2.25	-2.66	-2.26
Mining	0.18	0.14	0.14	0.30	0.99	0.43	1.63	2.95	0.65	2.81	3.00	-1.54	-1.65	-2.81	-2.98
Other Manufacturing[42]	0.01	0.01	-0.09	0.49	-1.00	0.30	1.34	-3.00	2.99	-1.82	3.00	-0.48	-1.53	-3.00	-2.63
Pulp and Paper	0.31	0.59	-0.34	-0.50	*	0.41	0.81	-3.00	2.95	3.00	-3.00	-1.38	-2.16	-2.27	-3.00
Energy Supply															
Crude Extraction	-0.07	-0.20	-0.07	0.45	*	0.02	0.30	•	1.01	•	•	-0.74	-0.34	-2.99	•
Electricity	0.20	*	0.26	0.35	-0.07	•	*	*	*	2.13	•	•	-0.99	-2.49	-1.34
Coal Mining	0.39	0.17	-0.05	0.64	0.32	1.34	1.44	3.00	0.99	3.00	0.61	-2.83	-2.27	-3.00	-3.00
Petroleum Refining	-0.10	0.46	-0.15	-0.32	*	-0.57	-0.10	*	2.76	•	•	-2.11	-2.28	-2.70	•
NG Extraction & Trans.	-0.26	-0.27	-0.25	•	*	0.91	•	*	*	*	*	-0.26	-0.13	•	•

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[42] The ISTUM Other Manufacturing model includes only those portions of manufacturing that directly use energy, a small portion of the cost of the sector.

In Table 23, the largest and smallest values are 3 and –3. The translog estimation process produces a response surface of varying elasticities that may take any value from plus to minus infinity. The pseudo data method brings out this response surface explicitly. If there is an abrupt change in an ESUB relationship moving from one price to another, this value can go asymptotically up or down, obscuring other less extreme parts of the response surface once weighting and averaging takes place. Three was chosen as a limiting elasticity, or slope in the response surface, but the value could also have been 2.0 or 3.5; this value was chosen as the maximum because it represents a boundary between highly and infinitely elastic demand (or inelastic in the case of –3). This issue raises some questions about the standard CGE approach of using constant elasticity equations, which I explore in the discussion section.

An important point in interpreting the elasticity results is that the national aggregates are weighted by costs (see Appendix G for the cost shares for individual fuels). For example, roughly 90% of all expenditures on petroleum products are in the transportation sector, approximately $49 billion, while roughly 50% of all expenditures on energy are in transportation, approximately $54 billion. Therefore, transportation's measured elasticities dominate the weighted calculation used to create the aggregate value. Transportation's measured own-price elasticity for petroleum products is –0.10, which is very inelastic, while for most other sectors it is roughly –2 or –3, or very elastic. The national aggregate estimate for the own-price elasticity for refined oil products including transportation is –0.35, and –2.74 when it is excluded.

Observations that emerge from the simulated sub-sector ESUBs in Table 23 (and Appendix G where noted) include:

- Inter-fuel substitutability is much greater than capital for energy substitutability. Specifically, the estimates for the electricity for natural gas ESUB (1.91), electricity for oil ESUB (1.73), natural gas for oil ESUB (1.27), natural gas for coal ESUB (0.95) and coal for oil ESUB (1.29) all suggest that inter-fuel substitutability is a promising direction for de-carbonization of the economy, relative to energy efficiency.

- The commercial and institutional sector, residential sector, electricity production, coal mining and industrial minerals sector in CIMS display the highest capital for energy ESUBs, which while still weak, offers opportunity for improved energy efficiency through technical substitution.

- The capital for electricity relationship offers the most potential for substituting away from energy. The sectors with the most capital for electricity substitution potential are pulp and paper, residences, petroleum refining, commerce and coal mining. Electricity expenditures are $33 billion in 1995 $'s in 2030, just under a third of the total of energy expenditures (Appendix G).

- There is some capital for natural gas substitution potential in electricity, metal smelting, and iron and steel. Natural gas expenditures are $18 billion in 1995 $'s in 2030, about 1/5 of total energy expenditures (Appendix G).

- The transportation market for gasoline dominates the national capital for refined petroleum products ESUB estimate and has little potential for improved efficiency. Most other sectors display weak to moderate substitutability, which suggests some small promise for energy efficiency. Refined petroleum products expenditures are the largest for all energy forms at $57 billion in 1995 $'s in 2030 (Appendix G).

- Coal is relatively unimportant in terms of expenditure on a national scale, but extremely important to a couple of sectors and to national carbon emissions. 72% of coal is burned in the electricity sector to produce steam to drive turbines to make electricity, while another 22% is used in the iron and steel sector, both for process heat and for adding carbon to steel. The iron and steel and electricity sectors' capital for coal ESUB is one of weak complementarity.

An unforeseen but potentially valuable feature of the parameter estimation experiments is their utility as a diagnostic for the technology dynamics of CIMS. I have already mentioned both the unresponsiveness of the transportation model to fuel price changes and the very high level of inter-fuel substitutability – the estimation process highlights these phenomena and makes them measurable. This will be addressed further in the discussion and conclusion chapters.

4.3 Using CIMS: Cost curves of abatement for Canada

Two different sets of "cost curves" results are presented. These results demonstrate both the effects of including structural change feedbacks with CIMS' sub-models, and the utility of this modelling approach to policymakers compared to the CGE and bottom-up approaches. The first set of results is a simpler exercise in which five GHG tax levels ($10, $25, $50, $100, $150) are run with four different levels of structural change feedbacks to show their varying effects. The second set of results are taken from two studies that were done with CIMS, studies that also include: 1) an in-depth analysis of the sources of emission reductions, or "actions", 2) actions exogenous to the model, and 3) a full analysis of costs. All results may be seen in the light of Canada's obligation to reduce

GHG emissions by 6% from 1990 levels by 2010. Current forecasts project this amount to be a reduction of 238 megatonnes (Mt) of CO_2e from the base case. Canada had been allowed 18 Mt of forestry and agricultural sinks, reducing the emissions reduction requirement to about 220 Mt.

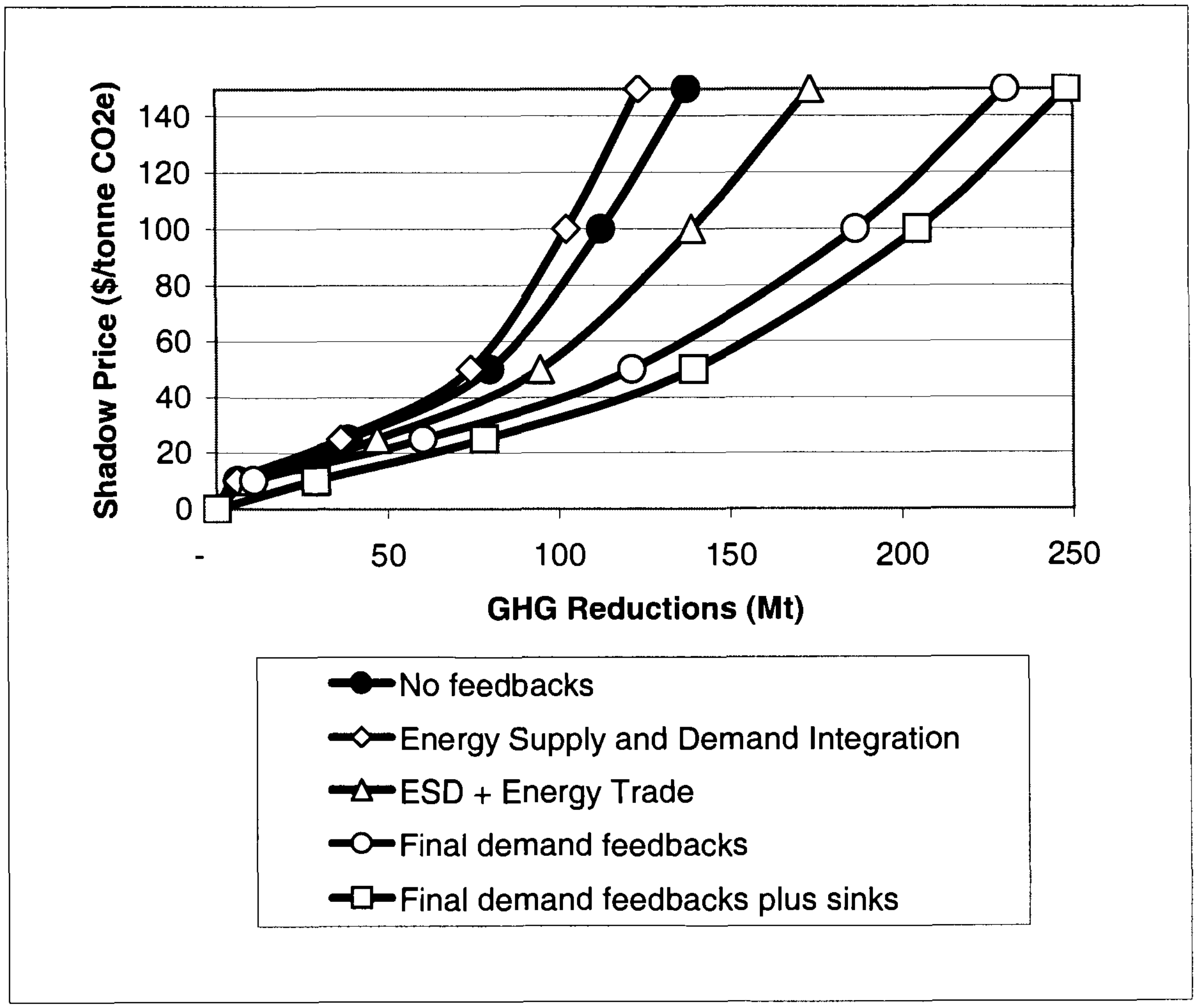
4.3.1 Cost curves of abatement under four levels of structural change feedbacks

This exercise provides cost curves of GHG emissions abatement for Canada for four different levels of structural change feedbacks: none, energy supply and demand integration, the latter plus energy trade, and full final demand feedbacks. Agricultural and forestry sinks, which are treated exogenously from CIMS, are added as a final step. The purpose of this exercise is to demonstrate the supplementary effects of each level of structural change feedbacks (Table 24 and Figure 10).

Table 24 Cost curves with different structural change feedback levels for Canada

Shadow price	**No feedbacks**	**Energy Supply and Demand Integration***	*** Plus Energy Trade Feedbacks**	**All feedbacks****	**** plus agricultural and forestry sinks**
($ / T CO_2e)	**Mt CO_2e of emissions reduced**	**Mt CO_2e of emissions reduced**	**Mt CO_2e of emissions reduced**	**Mt CO_2e of emissions reduced**	**Mt CO_2e of emissions reduced**
10	6.20	5.94	10.03	10.94	28.94
25	38.40	36.21	46.83	60.28	78.28
50	79.88	74.22	94.55	121.40	139.40
100	112.55	102.44	138.91	186.53	204.53
150	137.67	123.61	173.49	230.34	248.34

Figure 10 Cost curves with varying levels of feedbacks



No feedbacks provide the base case. Energy supply and demand integration increases GHG emissions at all GHG prices in relation to the no feedback case. This counter-intuitive result makes sense when one considers that, with no feedbacks, the consumer's price for electricity does not adjust in step with changes in the cost of producing it. Electricity is a GHG-free energy carrier for consumers, who will preferentially use more of it and less of natural gas, coal, and oil products as the charge for GHG emissions rises, if the price of electricity remains the same. In the no feedbacks case, if electricity is made by burning fossil fuels, or if it has a rising marginal cost curve, these higher costs are not passed on as higher electricity prices to end users. Energy supply and demand integration, in contrast, introduces these cost and pricing feedbacks, reducing the tendency of consumers to substitute electricity for direct consumption of fossil fuels.

Including energy trade has a significant effect on GHG emissions. Canada's main energy trade flows are the shipment of natural gas, crude oil, and electricity to the United States. Canada's exports of natural gas and crude oil entail several significant domestic sources of GHG emissions. Key amongst these is leakage from pipelines as well as consumption of natural gas to drive the compressors that propel the natural gas through the pipelines. Export demand for natural gas is somewhat elastic (an elasticity of –0.67 was used, with –1.34 being the point long-run estimate), and application of GHG pricing to the production and transmission of natural gas will increase its cost of production, reduce its demand, and thus reduce the associated emissions.

Electricity trade is a bit of a conundrum. At present most exports are from provinces with hydro power base production (Québec, Manitoba, British Columbia and from Labrador through Québec), with minimal GHG emissions. Most large, good quality hydropower sites are already in use, however, and most future marginal production will come from consumption of fossil fuels. Were domestic GHG emission reduction efforts to focus on inter-provincial transfers, or if the economics of North American electricity production made it profitable to either sell all the hydroelectricity or keep it all in Canada, the electricity trade patterns could change markedly. Average pricing is assumed in the results presented, and exports fall as appropriate to the region (not at all from Quebec or Manitoba, and a little bit from British Columbia) and GHG price.

Introducing final demand feedbacks increases emission reductions at all prices, because the increased cost of production raises prices and reduces final demand, thus reducing overall emissions. The sectors that contribute most to this are the industrial minerals and chemicals sectors, both of which produce significant process emissions. Demand reductions are limited to 50% of the base case: industrial minerals declines to this level by \$50 / t CO_2e and chemicals by \$75 / t CO_2e. Most other sectors do not suffer significant reductions (more than 3-5%) until the price of GHGs is well past \$75/ t CO_2e.

Canada has been allowed approximately 18 Mt in forestry and agricultural sinks under the Kyoto Protocol. These reductions show up at all GHG price levels, and their effect on Canada's costs curve is shown for illustrative purposes. \$150 / t CO_2e with demand feedbacks provides about 230 Mt of reductions, just short of Canada's Kyoto obligations, while including sinks raises this to 248 Mt, just over the required level of 238 Mt. Thus, Canada reaches its climate change obligations, a reduction of approximately 238 Mt from projected baseline levels with current estimates, at around \$130-150 / t CO_2e .

4.3.2 Separation of the effects of GHG intensity and direct and indirect structural change

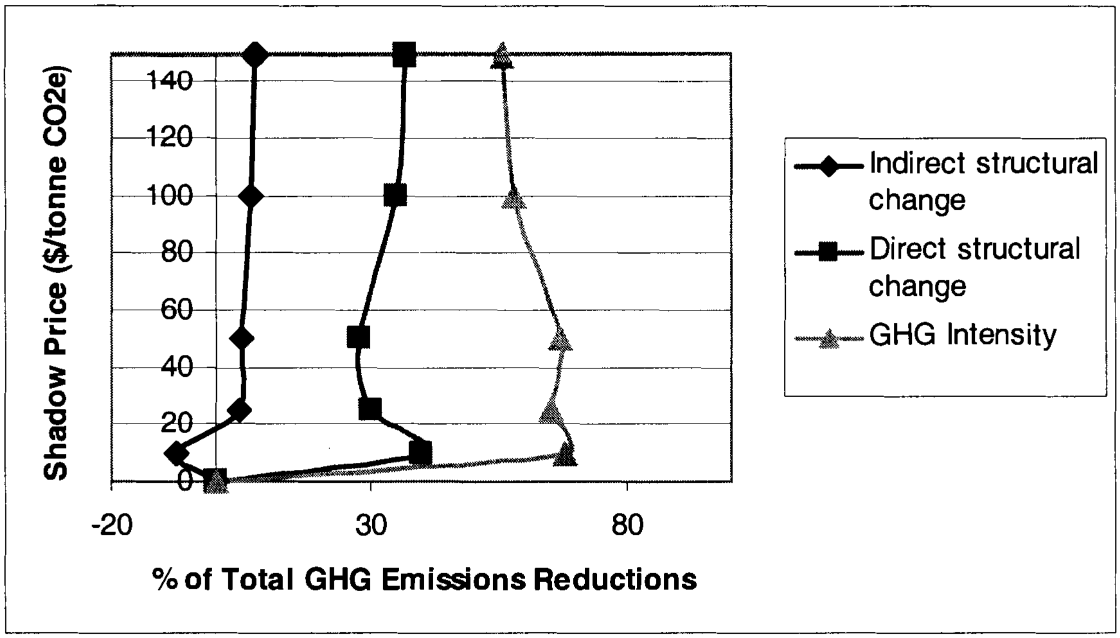
Loulou and Kanudia (2000) raised the question of the relative importance of technological adjustment (GHG intensity), direct and indirect structural change to GHG emission reductions – what proportion of the reduction did each component contribute? Bottom-up models specialize in the GHG intensity component while usually ignoring the structural change component, while CGE models specialize in the structural change component while accommodating the GHG intensity component through AEEI and ESUB. If all three components matter (GHG intensity, direct and indirect structural change), then policymakers need to use models that address all three. In an attempt to address the question of relative importance, I have taken the full feedback runs from the comparative feedbacks exercise and separated out the GHG intensity, direct and indirect structural change components of the GHG emission reductions for the five GHG tax levels (Table 25 and Figure 11).

The GHG intensity component of the emissions reductions for all sectors is composed of the technical efficiency and fuel switching adjustments to policy. It is calculated by dividing emissions by physical production (the number of units of goods or services produced) to find the BAU and Policy GHG intensities, taking their difference and then multiplying this by physical production under Policy. The direct structural change component is the result of the changes in demand for all goods and services, except those for the commercial/institutional and residential sector. It is calculated by subtracting the Policy physical production from the BAU physical production, and multiplying the result by the BAU GHG intensity. The indirect structural change component is the result of the adjustments to disposable income, savings (multiplier) and other indirect structural effects. It is simulated in CIMS by linking demand in the commercial / institutional and residential sectors to manufacturing value-added in all the other sectors. It is calculated as the direct structural change component of GHG reductions for the commercial, residential and freight sectors; the GHG intensity component of these sectors is counted as a GHG intensity change. There is a bias toward the indirect structural change effects being relatively smaller than they actually might be, as this method captures only a subset of the second order effects.

Table 25 Separation of the GHG intensity, direct and indirect structural change effects on GHG emission reductions at 5 tax levels, 2010

Shadow Price ($ / T CO_2e)	Total reduction in GHGs (Mt)	GHG Intensity (Mt)	% of total reduction in GHGs	Direct structural change (Mt)	% of total reduction in GHGs	Indirect structural change (Mt)	% of total reduction in GHGs
10	6.85	4.63	68%	2.74	40%	-0.52	-8%
25	49.66	32.35	65%	14.96	30%	2.36	5%
50	101.07	67.61	67%	28.42	28%	5.04	5%
100	150.06	86.88	58%	52.74	35%	10.43	7%
150	180.46	100.06	55%	66.42	37%	13.97	8%

Figure 11 **Relative contribution of changes in GHG intensity, direct and indirect structural change to GHG emissions reductions at $10, $25, $50, $100 and $150, 2010**



In Table 25 and Figure 11 the relative shares of each of GHG intensity, direct and indirect structural changes are presented additively, such that their shares add to 100%. Thus for the $10 tax rate GHG intensity provides 68% of reductions, direct structural adjustment 40% and indirect structural adjustment adds 8% relative to BAU (effectively –8%), for a sum of 100%.

GHG intensity adjustment always provides the largest share of emissions reductions, but is overwhelmingly dominant at the lower tax rates (68% at $10). In general, this suggests the economy can sustain some investment to reduce GHG emissions without demand declining by much in most sectors. Direct structural adjustments initially contribute a lot (40% at $10), then less (30% at $25), and then progressively more. Indirect structural adjustments start by increasing emissions at $10. This is because at the lowest tax rates the cost of production in manufacturing rises faster than demand falls, leading to increased value-added in that sector. This in turn leads to a small increase in commercial and residential activity. This effect disappears as the tax rate rises. Emissions reductions due to indirect structural change increase steadily in relative size, but remain at less than 10% for all tax levels.

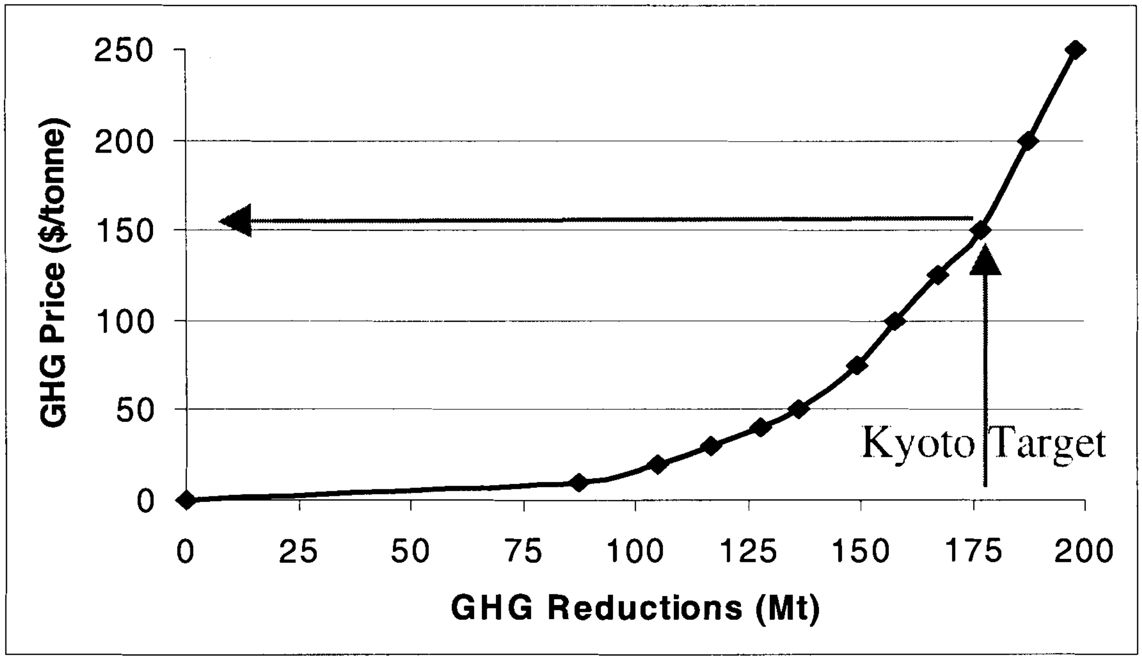
For comparison, Schreper and Kram (1994) found that if a 50% GHG emission reduction were modelled in MARKAL-MACRO, 84% of reductions came from GHG intensity, 13% from direct structural change, and 3% from indirect structural change. I find more effect from both direct and indirect structural change effects, especially direct effects. This might be explained by the methodological difference between CIMS and MARKAL with respect to representing technology choice behaviour. In CIMS, consumers and firms require higher taxes to choose less carbon intensive equipment relative to MARKAL. The higher cost of production that results creates more direct and indirect structural effect as consumption shifts away from sectors that are particularly hard hit by the higher taxes. The relative importance of the effects change with the GHG tax rate, however, and are likely to adjust with other energy polices. In general, GHG intensity changes matter more with modest policies, and less with more aggressive ones, with direct and indirect structural change effects increasing with the aggressiveness of the policy.

4.3.3 Results of two full scale cost curves exercises

CIMS was applied to estimate GHG abatement costs for two different policy exercises for Canadian policy makers. The first exercise, "Construction and Analysis of Sectoral, Regional and National Cost Curves of GHG Abatement in Canada" (Bataille *et al.* 2002), found the emission reductions and costs associated with 11 different GHG prices, and analyzed the actions that caused the abatement. The second (Laurin *et al.* 2003) added updated data and final demand feedbacks. These exercises differ from the feedback comparison in that they include a set of exogenous actions specified by the stakeholders in the national climate change process and full cost reporting. The purpose of this section is to demonstrate the special utility of CIMS to policymakers compared to the bottom-up and CGE approaches, specifically the technological detail missing from the CGE approach and the behavioural and equilibrium feedback realism missing from the bottom-up approach. In both exercises the GHG tax is considered to be a revenue neutral transfer to the government from the consumers of products which released GHGs in their production, and as such is an intra-societal transfer that nets to zero. The tax is revenue neutral in that it displaces other taxes, which opens up the question of tax recycling effects, but these were not considered in these studies.

Figure 12 provides the national cost curve for the first cost curves study where, at any particular shadow price associated with GHG emissions (y-axis), the quantity of emissions reduced can be determined (x axis).[43]

Figure 12 Cost curve of GHG emissions abatement in Canada with energy supply and demand integration



The purpose of the first study was to find out what emissions reductions are available in the Canadian economy at the given GHG prices, right up to the price where Canada achieves domestically all of its climate change emissions reductions goals, 6% below the 1990 level by 2012. The closest cost curve run to the Kyoto target, a reduction of 178.7 Mt based on Natural Resources Canada's "Canada's Energy Outlook: An Update" (CEOU), is the $150 run with a reduction of 176.6 Mt. At this GHG price the electricity sector delivers 83 Mt (47%), mainly through underground sequestration of power plant emissions and

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[43] This figure is from before the national GHG inventory of emissions was revised upward.

switching from coal to natural gas electricity generation in Alberta and Saskatchewan, transportation 28.7 Mt (16%), industry (excluding natural gas extraction) 26.2 Mt (14.8%), natural gas extraction 10.4 Mt (5.9%), commercial 9.7 Mt (5.5%), residential 8.0 Mt (4.5%), agriculture 8.5 Mt (4.8%) and afforestation 2 Mt (1.1 %). Transportation achieved its reductions through fuel switching and switching between single occupancy, high occupancy, transit, walking, and cycling (mode switching). Industry gets its reductions mainly through process changes, fuel switching and energy efficiency. Commercial's reductions came through flaring of landfill gas, whereby methane (a strong GHG) is turned into CO_2 (a lesser GHG) and is sometimes used to generate electricity via cogeneration. It also achieved large reductions through energy efficiency actions. Residential gets it reductions through fuel switching, depending on the relative fuel prices in a given region, and through energy efficiency. In this exercise, natural gas and petroleum prices and production were constant. Any surplus was to be exported, and any deficit imported.

Table 26 defines the energy saved, GHG emissions reduced, techno-economic costs (TEC), expected resource costs, (ERC) and perceived private costs (PPC) associated with the reductions with each of the GHG prices. In this table, all TEC values include the electricity sector's techno-economic costs but exclude the effects of changing electricity prices.

Table 26 Energy, emissions and costs associated with emissions reduction in Canada, 2010

Shadow price	Energy Saved	Emissions Reduced	TEC w/o Trans Sector	TEC, All Sectors	TEC w/ Parked Vehicle Costs	ERC, All Sectors	ERC w/ Parked Vehicle Costs	Perceived Private Costs
($ / T CO_2e)	(PJ)	(Mt)	(’95$ billion)	(’95$ billion)	(’95$ billion)	(‘95$ billion)	(‘95$ billion)	(’95$ billion)
10	941	87.6	(25.2)	(30.0)	(28.7)	(5.9)	(5.6)	2.1
20	1,028	105.0	(23.6)	(30.5)	(28.0)	(2.5)	(1.8)	6.9
30	1,098	116.7	(21.3)	(30.3)	(26.5)	1.8	2.8	12.5
40	1,172	128.0	(19.1)	(29.9)	(24.8)	6.5	7.8	18.6
50	1,232	136.2	(16.4)	(29.2)	(22.9)	11.6	13.2	25.2
75	1,298	149.1	(10.7)	(28.0)	(18.7)	25.3	27.6	43.0
100	1,354	157.6	(7.1)	(28.7)	(16.4)	39.4	42.4	62.1
125	1,402	167.2	(3.7)	(28.7)	(13.5)	54.4	58.2	82.1
150	1,450	176.6	0.2	(25.9)	(7.9)	70.7	75.2	102.9
200	1,539	187.2	9.7	(22.9)	0.4	104.2	110.0	146.5
250	1,627	198.0	18.9	(17.6)	10.8	140.1	147.3	192.7

Transportation costs are represented differently than the other sectors. Transportation has very large negative techno-economic costs (i.e. benefits) because walking, cycling, transit and higher occupancy private vehicles cost less financially than single occupancy private vehicles. In the first TEC column in Table 26, the financial savings are excluded in the transportation sector. The second TEC column, which includes transportation, includes the negative cost (savings) of not buying vehicles. These savings are, however, accompanied by a substantial loss of consumers’ surplus. It is uncertain about the degree to which consumers who switch away from single occupancy vehicles would continue to purchase vehicles; national level TEC and ERC costs are provided to reflect the two contrasting assumptions. The costs in columns labeled "All Sectors" assume that a change in vehicle kilometres is accompanied by a corresponding change in vehicle ownership. The costs in columns labeled "with Parked Vehicle Costs" assume that individuals continue to purchase vehicles despite switching to other modes of transportation for portions of their travel. These are extremes to the range of possibilities.

Table 27 outlines the significant emissions reduction actions for all Canada at the $150 level; the importance of these actions at $10 is also provided. This list was established by setting a criterion of a minimum 1% contribution to total reductions at the $150 level. The relative importance of the actions could be different for every shadow price level; underground sequestration of GHG emissions from electricity production, for example, does not exist at $10 but is the second most important action at $150.

Table 27 The significant actions for Canada

All actions over 1% of total reductions at $150	$10 Mt	% of total at $10	$150 Mt	% of total at $150	Source [44]
Switch to high eff. boilers and gas turbines for elec. prod.	35.2	39.6%	30.0	16.9%	CIMS
Sequestration in electricity production	Nil	nil	24.5	13.8%	CIMS
Switch to hydroelectric electricity production	5.0	5.6%	16.0	9.0%	CIMS
Electricity demand reductions	9.8	11.0%	7.6	4.3%	CIMS
NG transmission - Replace turbines with electric drivers	4.1	4.6%	7.4	4.2%	CIMS
Commercial landfill gas	6.0	6.8%	6.0	3.4%	EXOG
Transportation mode switching	0.4	0.5%	4.9	2.8%	CIMS
Residential high efficiency furnaces and shell improvements	1.6	1.8%	3.8	2.1%	CIMS
Switch to non-hydro renewables in electricity	2.4	2.7%	3.7	2.1%	CIMS
Personal car efficiency improvements	0.3	0.3%	3.3	1.9%	CIMS
Transportation: F2B truck speed control	nil	nil	3.2	1.8%	EXOG
Sequestration of CO2 from hydrogen plants	2.8	3.2%	2.8	1.6%	EXOG
Agricultural grazing strategies	2.6	2.9%	2.6	1.5%	EXOG
Other manufacturing: Fuel switching for water boilers	nil	nil	2.5	1.4%	CIMS
Other manufacturing: Fuel switching for space heating	0.8	0.9%	2.4	1.3%	CIMS
Transportation: F8C accelerated truck scrappage	2.2	2.5%	2.2	1.2%	EXOG
Agriculture: Increased no-till	nil	nil	2.1	1.2%	EXOG
Fuel switching in residential space heating	1.2	1.4%	2.0	1.1%	CIMS
Transportation: K1 Off road efficiency standards	nil	nil	2.0	1.1%	EXOG
Transportation: F10 truck driver training in energy efficiency	1.9	2.1%	1.9	1.1%	EXOG
Residential hot water efficiency improvements	0.5	0.6%	1.8	1.0%	CIMS
Sum of national total reductions		86.5%		74.6%	

The most striking phenomenon is that the top four actions are from electricity production; the switch from coal boilers to high efficiency natural gas fired

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[44] EXOG means the action was specified exogenously Canada's National Climate Change Process table stakeholders.

combined cycle turbines delivers the largest amount of reductions of any action. Of these actions, sequestration presents perhaps the most questions concerning its maturity and costs. Another phenomenon is the importance of exogenously specified actions such as commercial landfill gas, truck speed controls and sequestration of CO_2 produced during hydrogen production. These actions penetrate fully once the shadow price level reaches its specified cost; if they were modelled in CIMS, their advent would likely start at a lower shadow price but their penetration would be much more gradual. A brief summary of the actions is provided below.

Switch to simple and combined cycle gas turbines in the electricity production sector

Switching from coal boilers to simple and combined cycle gas turbines for electricity production provides 21.0 Mt through increased energy efficiency, and 9 Mt through fuel-switching, for a total of 30.0 Mt at $150 (16.9% of national reductions at $150). The difficulty with implementing this action is that electricity demand falls or is stagnant in the provinces (Alberta, Saskatchewan and Ontario) where this action will have the most effect. The newer, cleaner equipment would have to be retrofitted in place of older equipment, a significant cost to producers.

Sequestration in electricity and hydrogen production

Large reductions come from the sequestration of emissions from coal-fired electricity supply (24.5 Mt, 13.8% of the national total at $150). Utilization of sequestration on this scale requires that key technologies, such as hot filtration of power plant exhaust gases, mature soon. Sequestration from hydrogen production does not require hot filtration and can commence using current technology; it contributes 2.8 Mt at any price level as it is an inexpensive exogenously defined action, or 1.6% of national reductions at $150.

Switch to hydro-powered electricity production

Choosing hydroelectric power over fossil fuel alternatives provided the third largest reduction. There are, however, many uncertainties and issues associated with this action, such the declining availability of new sites, public acceptance and up-front capital costs.

Switch to non-hydro renewables in electricity production

Occurring to a significant extent in Ontario, wind, solar and biomass contributes 2.4 Mt at $10 and 3.7 Mt at $10, or 2.7% and 2.1 % of national reductions.

Commercial, Residential and Industrial electricity energy efficiency programs

Electricity demand from the commercial, industrial, and residential sectors falls considerably, both from efficiency and self-generation. Avoided emissions related to these reductions in electricity demand amount to 7.6 Mt at $150.

Natural Gas Transmission – Replace turbines with electric drivers and leak detection and repair programs

The issue table for natural gas production identified an emission reduction action whereby the transmission compressors that move the natural gas are switched from natural gas to electricity. The efficacy of this action depends on the price of electricity – it penetrates much further in the provinces with lots of inexpensive hydroelectric generation. This single action saves 7.4 Mt, or 4.2% of the national reductions at $150. Leak detection and repair was also identified as a potential action; methane, the primary component of natural gas, is a strong greenhouse gas, twenty-one times more potent than CO_2. Actions to reduce leakage contribute 1.3 Mt of reductions at $150.

Commercial landfill gas capping, flaring and cogeneration

The decomposition of garbage emits enormous quantities of the methane. If this methane were captured and burned to generate electricity, it would reduce 6.0 Mt of direct reductions at all GHG prices (3.4% of all emission reductions at $150), not including reduced indirect emissions from electricity.

General transportation mode shifting and efficiency

While a critical analysis of transportation demand shows little willingness to travel less, there are potential reductions via mode switching. This would be mainly a movement from single to high-occupancy vehicles; there would also be some movement from private vehicles to transit, cycling and walking. This potential is, however, associated with very large losses of consumers' surplus. Mode shifting and personal car efficiency improvements contribute 4.9 and 3.3 Mt, or 2.8% and 1.9% of national reductions at $150.

Several important transportation measures were modelled exogenously from CIMS. These include off-road efficiency standards (0 Mt at $10, 2.0 Mt at $150), truck driver training in efficiency (1.9 Mt at both $10 and $150), accelerated truck scrappage (2.2 Mt at both $10 and $150) and truck speed controls (0 Mt at $10, 3.2 Mt at $150).

Residential high efficiency furnaces, fuel switching, hot water and shell improvements

The combined effects of high efficiency furnaces and shell improvements in the residential sector contribute 3.8 MT, or 2.1% of the national total at $150. Fuel switching to natural gas and electricity contributes another 2.0 Mt, or 1.1% of national reductions. Hot water efficiency contributes another 1.8 Mt, or 1.0 % of national reductions at $150.

Fuel switching for water boilers and space heating in Other Manufacturing

Switching to natural gas and electricity for water boilers and space heating contributed 2.5 and 2.4 Mt (1.4 % and 1.3%) respectively.

Improving the agricultural sink

Agriculture is a major source of GHGs through normal practices that induce the breakdown of living plant life. These emissions can be significantly reduced via strategies that maintain the maximum amount of living biomass: changes in grazing strategies, no-till farming, etc. The improvements contribute 5.5 Mt at negative cost at $20 / t CO_2e and only develop positive costs at $30 / t CO_2e. They contribute their full 8.5 Mt at $75.

Fuel switching in general

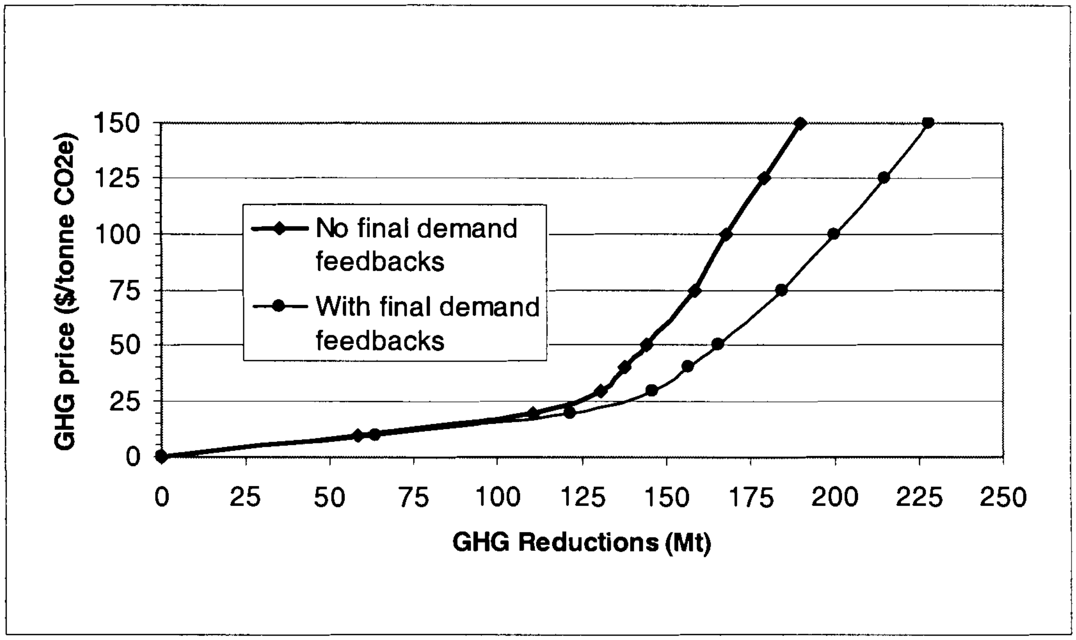
Fuel switching from more to less carbon-intense fuels, and from fossil fuels to electricity in general, plays an enormous part in reducing GHG emissions. It is a difficult matter to separate the effects because switching from one technology to another can carry both efficiency and fuel switching characteristics with it, and allocation to these two components is not simple.

The initial cost curves work was succeeded by another (Phase 2, Laurin *et al.* 2003) in which three key changes were made: the data was updated for a new start year in 2000 as opposed to 1995, final demand feedbacks were added and a new emission forecast from the federal government was used. I focus here on a comparison of the results with and without the goods and services demand feedbacks, with one caveat. The method used to prepare the simple cost curves exercise and the AEEI and ESUB estimates applied goods and services demand adjustments specific to individual products. In contrast, the method used in the Phase 2 analysis is from an earlier period when the goods and services feedbacks raised and lowered demands for sub-sectors as whole, ignoring the product distinctions within them (such as between lime and cement in Industrial Minerals, or rubber goods, textiles and transportation equipment in Other Manufacturing). Another difference is that in Phase 2 final demand for residences and the commercial and freight transportation sectors was driven using demand elasticities instead of the current method of linking their demand to general economic activity, using manufacturing value-added as proxy. The sum difference of all these changes is that the demand feedbacks in Phase 2 were somewhat distorted and smaller in magnitude than they otherwise would have been.

Figure 13 shows the cost curve for Canada for Phase 2 with and without structural change at $10, $30, $50, $100, and $150. GHG reductions are greater at all tax levels with final demand feedbacks, as GHG pricing increases the cost of most goods, decreasing their demand, production and inherent emissions.

The effects are negligible at the lowest taxes, are visibly substantial around $15-20 / tonne, and increase with the GHG tax after that.

Figure 13 Cost curves of GHG emissions for Canada in Phase 2 with and without final demand feedbacks, 2010.



Tables 28 and 29 provide the GHG and energy reductions and costs in Phase 2 with and without final demand feedbacks.

Table 28 Phase 2 energy, emissions and cost results (2010), Canada, without final demand feedbacks.

Shadow price	Energy Saved	Emissions Reduced	TEC w/o Trans Sector	TEC All Sectors	TEC w/ Parked Vehicle Costs	ERC, All Sectors	Perceived Private Costs
($ / T CO_2e)	(PJ)	(Mt CO_2e)	('95$ billion)	('95$ billion)	('95$ billion)	('95$ billion)	('95$ billion)
10	661.5	57.7	-8.9	-14.3	-13.2	-1.6	2.5
30	1,105.0	130.3	-4.6	-16.1	-12.8	5.2	12.4
50	1,192.0	144.1	-2.9	-20.0	-14.6	14.5	26.2
100	1,304.0	168.4	1.2	-29.3	-18.7	41.6	65.3
150	1,377.0	190.4	6.5	-32.4	-16.9	73.4	108.7

Table 29 **Phase 2 energy, emissions and cost results (2010), Canada, with final demand feedbacks**

Shadow price	Energy Saved	Emissions Reduced	TEC w/o Trans Sector	TEC, All Sectors	ERC, All Sectors	Perceived Private Costs	Loss of Consumers' Surplus
($ / T CO_2e)	(PJ)	(Mt CO_2e)	('95$ billion)	('95$ billion)	('95$ billion)	('95$ billion)	('95 $billion)
10	738.5	63.6	-14.1	-19.8	-2.9	2.7	5.0
30	1,326.2	146.4	-20.8	-33.2	1.9	13.4	16.0
50	1,517.8	165.6	-28.4	-47.0	9.7	28.7	26.5
100	1,856.2	200.5	-45.0	-78.4	36.1	73.4	50.9
150	2,115.1	228.4	-61.2	-104.2	68.2	124.5	75.1

The final column of Table 29 is an indicator of change in consumers' surplus. Consumers' surplus loss represents the lost consumer welfare associated with reduced residential expenditure and mobility.

Table 30 contains estimates of loss of value-added (sector GDP) and changes in financial investment. It is calculated from the 10 years from 2000 to 2010 in $1995 dollars, discounted back to 2000. The next two columns show the two components of net change in financial investment in CIMS relative to BAU. The cost of production component captures the internal capital investment and fuel choice adjustments of the model, or the TEC costs endogenous to the model. The change in output component captures the effects of the elastic demand / macro-economic system, or the reductions in output from BAU. The final column shows the sum of these two components. This sum excludes the costs of exogenous actions but includes electricity price increases faced by the demand sectors.

Table 30 Net change in financial investment in 2010, Canada, with final demand feedbacks.

		Net Change in Financial Investment		
Shadow Price	Reduction in Value-Added	Cost of Production Component	Change in Output Component	Total
($ / T CO_2e)	('95$ billion)	('95$ billion)	('95$ billion)	('95$ billion)
10	7.1	18.5	-17.3	2.0
30	13.3	40.5	-41.6	4.2
50	19.9	52.2	-59.5	-0.8
100	35.6	71.4	-99.7	-20.0
150	49.2	88.8	-136.8	-38.7

Tables 31 and 32 show the effect on GHG emissions of integrating final demand feedbacks when simulating shadow price levels. Table 31 provides physical output in 2010 at $150/tonne as a percentage of BAU.

Table 31 Demand in 2010 as a percentage of BAU with a $150/tonne GHG price

Sectors	Regions						
	BC	AB	SK	MB	ON	PQ	MT
Demand							
Commercial and Inst.	99%	96%	94%	99%	98%	98%	99%
Residential	89%	69%	93%	99%	98%	99%	90%
Transportation	99%	99%	99%	99%	100%	100%	99%
Industry							
Chemical Products	94%	50%			63%	91%	
Industrial Minerals	50%	50%			50%	50%	50%
Iron and Steel					84%	94%	
Metal Smelting	83%			89%	83%	85%	50%
Mining	93%		50%	92%	86%	88%	85%
Other Manufacturing	79%	71%	83%	95%	85%	95%	93%
Pulp and Paper	73%	72%			62%	79%	79%
Energy Supply							
Crude Extraction	100%	100%	100%		100%		100%
Electricity	92%	78%	79%	99%	89%	95%	98%
Coal Mining	101%	39%	6%				6%
Petroleum Refining	100%	100%	100%		100%	100%	100%
Natural Gas	100%	100%	100%	100%	100%	100%	100%

In Table 32, the sectors have been presented in descending order of sensitivity to the inclusion of final demand feedbacks, based on the $10 shadow price.

Table 32 The effects of integrating final demand feedbacks.

Shadow Price	10	30	50	100	150
	Mt of CO_2e				
BAU (Endogenous emissions)	683.0	683.0	683.0	683.0	683.0
National Reductions w/o macro	34.1	96.4	108.5	130.5	146.3
National Reductions w/ macro	39.9	112.5	130.1	162.6	184.3
Difference	5.8	16.1	21.6	32.1	38.0
	% of difference between GHG reductions w/ and w/o macro by sector				
Industrial Minerals	35%	38%	32%	21%	17%
Chemical Production	21%	22%	27%	35%	35%
Electricity Production	23%	14%	12%	10%	7%
Other Manufacturing	6%	6%	7%	9%	11%
Residential	4%	5%	6%	7%	8%
Iron and Steel	3%	3%	4%	5%	6%
Metal Smelting	3%	2%	3%	3%	4%
Mining	3%	3%	3%	2%	2%
Transportation	1%	1%	2%	2%	3%
Commercial	1%	1%	1%	1%	1%
Pulp and Paper	0%	3%	4%	5%	7%
Crude Extraction	0%	0%	0%	0%	0%
Coal Mining	0%	0%	0%	0%	0%
Refineries	0%	0%	0%	0%	0%
NG Extraction and Transmission	0%	0%	0%	0%	0%

Three sectors stand out for having strong responses: industrial minerals, chemical production, and electricity production. Other Manufacturing, Residential, Pulp and Paper, Iron and Steel, Metal Smelting and Mining are moderately affected. The energy supply models (besides Electricity), Commercial and Transportation are largely unaffected.

The Industrial Minerals sub-sector is strongly affected because the cost of production rises steeply due to heat requirements and process emissions and foreign produced cement is easily substituted for domestic production. Output falls an average 15% across the country at the $10 levels, and keeps falling at higher shadow prices. The response is so strong, leading to the industry disappearing across the country, that output dropped to the limit of –50% from BAU.

The chemical products sub-sector, while having on average a relatively inelastic demand with an Armington price elasticity of -0.44, has very large increases in production costs due to process emissions associated with ammonia synthesis and ethylene cracking. The strongest effects are in Alberta, and to a lesser degree in Ontario. Output falls 5% in Alberta at the $10 level and drops 44% at the $100 level. As for Industrial Minerals, a maximum drop in output of 50% was set, which was seen just above the $100 shadow price level.

Electricity production's relatively high degree of sensitivity to inclusion of final demand feedbacks is due to the combined effects of the nominally smaller changes to Residential (-4% at $10), Other Manufacturing (-6% at $10) and the other industrial sectors. Its relative importance falls with increasing GHG prices.

Along with changes in emissions, changes in direct value-added are presented for the manufacturing sub-models. Value-added, as discussed earlier, is used instead of output because of the possibility of double counting. Crude oil extraction only includes value-added associated with actions endogenous to the model. Table 33 shows estimates of loss of value-added over the 10-year period, 2000-2010, from highest to lowest based on the \$50 CO_2e price. Positive values represent value-added losses.

Table 33 Loss of direct value-added with final demand feedbacks over 10-year period.

	Loss of value-added (\$1995 billions, 2000- 2010)				
	10	**30**	**50**	**100**	**150**
Industrial Minerals	1.1	3.7	5.2	6.5	6.4
NG Extraction and Transmission	2.3	3.6	4.6	6.3	7.5
Pulp and Paper	0.5	2.1	3.6	8.0	13.0
Refineries	0.1	1.7	2.7	4.6	6.5
Iron and Steel	0.5	1.5	2.5	5.1	7.9
Coal Mining	-0.1	2.2	2.3	2.2	1.9
Metal Smelting	0.3	1.0	1.8	3.6	5.6
Chemical Production	0.0	0.6	1.6	4.6	6.9
Mining	0.2	0.9	1.4	2.6	3.7
Endogenous Crude Extraction	0.0	0.2	0.4	0.6	0.7
Electricity Production	3.5	-0.4	-1.5	-3.1	-4.0
Other Manufacturing	-1.4	-3.8	-4.5	-5.6	-6.9
Total loss of direct value-added	**7.1**	**13.3**	**19.9**	**35.6**	**49.2**

The Industrial Minerals and Natural Gas Extraction and Transmission sub-sectors experience substantial value-added losses at the lower CO_2e prices. The Pulp and Paper sub-sector has slightly lower losses but above \$50 / t CO_2e has the largest losses among the industrial sub-sectors. Iron and Steel, Petroleum Refining, Chemicals and Metal Smelting experience moderate value-added losses of roughly the same magnitude at lower CO_2e prices but these losses grow steadily as the CO_2e price increases. Electricity production, on the other hand, experiences a large loss of value-added at the \$10 CO_2e price because the loss due to demand reduction exceeds the gain from increased revenue via the increased price. As demand for electricity rises back towards

BAU levels with increasing CO_2e prices, the gains from price increases outweigh the declining demand-related losses. Value-added increases significantly in the Other Manufacturing sub-sector in response to increasing CO_2e prices. This occurs because the cost of production (with implicit value-added) increased more than demand fell. These figures are net of carbon costs and do not include Transportation, or the Residential and Commercial sectors.

Table 34 summarizes the provincial changes in value-added. Quebec, Ontario, and Alberta experience the largest value-added losses and jointly represent over 75% of total value-added losses at each CO_2e price. British Columbia experiences moderate losses of value-added. The Atlantic regions and Manitoba experience fairly slight losses of value-added. Saskatchewan shows increases in value-added at most CO_2e prices due to value-added increases in the Other Manufacturing sub-sector and the electricity sector.

Table 34 Loss of direct value-added with final demand feedbacks over 10-year period.

	Loss of value-added ($1995 billions, 2000- 2010)				
	10	**30**	**50**	**100**	**150**
British Columbia	1.0	2.2	3.2	5.4	6.6
Alberta	1.6	3.6	5.1	9.0	12.4
Saskatchewan	0.1	-0.4	-0.4	-0.7	-0.8
Manitoba	0.3	0.3	0.3	0.2	0.1
Ontario	2.1	3.1	4.9	9.9	13.8
Quebec	1.7	4.0	6.2	10.3	14.7
Atlantic	0.2	0.3	0.7	1.5	2.4
Total loss of direct value-added	**7.1**	**13.3**	**19.9**	**35.6**	**49.2**

Table 35 shows the value-added losses in Table 34 as percentages of the estimated cumulative provincial and national GDP from 2000 - 2010.

Table 35 Loss of direct value-added with final demand feedbacks over 10-year period.

	Cumulative GDP estimate (2000-2010, $1995 billions, NPV'd to 2000)	Loss of value-added as % of Cumulative GDP				
		10	30	50	100	150
British Columbia	859	0.1%	0.3%	0.4%	0.6%	0.8%
Alberta	834	0.2%	0.4%	0.6%	1.1%	1.5%
Saskatchewan	216	0.0%	-0.2%	-0.2%	-0.3%	-0.4%
Manitoba	224	0.1%	0.2%	0.2%	0.1%	0.0%
Ontario	2,981	0.1%	0.1%	0.2%	0.3%	0.5%
Quebec	1,485	0.1%	0.3%	0.4%	0.7%	1.0%
Atlantic	393	0.1%	0.1%	0.2%	0.4%	0.6%
Canada	**6,992**	**0.1%**	**0.2%**	**0.3%**	**0.5%**	**0.7%**

Cumulative GDP is estimated by applying the GDP growth forecast in "Canada's Energy Outlook – An Update" to estimates of provincial GDP from the year 2000, generating GDP figures for each year from 2000 to 2010 and determining the net present value of these estimates in 2000 in 1995 dollars. The industrial and energy supply sectors produce a loss of 0.7% of cumulative national GDP at the $150 CO_2e price, at which the Kyoto target is very nearly met when final demand feedbacks are activated. Given the estimate from CIMS does not include losses of value-added for Residential, Commercial and Transportation, which showed declines in physical output of 6.6%, 2.2% and 0.6% respectively, it is similar to a study by Informetrica (2000). Starting with capital and energy expenditure figures from a CIMS run without demand feedbacks, Informetrica found an annual 3% loss in GDP for the whole economy with a GHG price of $150/tonne.

4.4 Results summary

The preceding chapter provided: 1) summaries of the AEEI and ESUB parameter estimations made with CIMS, 2) an estimated separation of the GHG reduction effects of GHG technical intensity, direct and indirect structural change using CIMS, and 3) costs curves of GHG abatement for Canada.

AEEI, with notable sectoral differences, was 0.44 %/year for Canada with transportation and 0.66 %/year without. The capital for energy elasticity of substitution (ESUB), again with notable sectoral differences, was 0.13 for Canada with transportation and 0.27 without. Structural change effects did not appreciably affect either parameter measurement. The experiments to separate the GHG intensity and direct and indirect structural change effects show that technical adjustments (GHG intensity) make up about half the response to simulated energy policy, and macroeconomic demand adjustments the other half. Technical adjustments predominate with minor policies, while the importance of the macroeconomic demand adjustment increases with the strength of the policy. The cost curves of abatement show Canada would have met its Kyoto Protocol commitments alone without trading were a charge of \$150 / tonne CO_2e imposed at the beginning of 2003.[45]

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[45] These reductions include the increased economic growth of late 1990's and the sinks agreed to at the Bonn and Marrakech meetings of UNFCCC.

5 Discussion

This chapter has three sections. In the first I discuss how well I met my design and construction criteria in creating CIMS from ISTUM. This is followed by an analysis of the AEEI and ESUB estimation and cost curves results. It finishes with a discussion of uncertainty in the results of the CIMS model.

5.1 How well did CIMS meet its construction criteria?

I set ten criteria for CIMS' design and construction, and they are here used to critique how well structural change feedbacks were incorporated into CIMS.

1. **The methods should be able to simulate equilibrium between energy supply and demand.**

Simulation of energy supply and demand equilibrium focuses on how the demand for electricity, natural gas, refined petroleum products, crude oil, and coal changes in response to policy. Because of CIMS' history as the ISTUM model, all the necessary components were available for linking energy flows from the end-use demand side of the economy to the energy supply side, with the exception of export and import flows. This linking exercise required some calibration between the individual components; for example, summed electricity demand from the end-use service and energy supply models in a given region does not usually add up exactly to the exogenously specified demand for the electricity model, hence the necessity for a calibration value to make them match.

These calibration values ensure that any difference between a policy and BAU run is due to the policy, and not miss-calibration between components. They may also be thought of as an "error term" that is a conglomerate of error in the exogenous forecasts for goods and services demand, the technologies used to meet this demand and coordination between energy supply and demand in the exogenous forecast.

Simulation of energy supply and demand equilibrium required that CIMS calculate changes in the market price for energy commodities in response to policies. Pricing was revealed as one of the major challenges of building the CIMS model. The first challenge emerged when endogenous pricing for electricity was installed. The principle was clear – use the ratio of the Policy and BAU per-unit production costs to modify the initial exogenously specified price. The unit cost of production is the total cost of production divided by the number of units produced. The difficulty is that the sub-models, as originally designed, do not cover the total cost of production. They cover the cost of fuel, the cost of capital associated with consuming energy, and the annual cost of labour. Some models even used relative costing measures unrelated to the absolute cost of production. None of the models cover the installation costs for capital not associated with consuming energy, purchased supplies or raw materials. In some sectors, the sub-models cover most of the costs, and in others less than 20%. The missing costs were measured by calculating the gap between historic total cost measured from statistical data and the cost covered by the sub-models. The measured gap was then incorporated into the pricing mechanism. The uncovered part of cost was assumed to be untouched by policy. The results produced by this system have been satisfactory in that they have made both empirical and intuitive sense.

2. **The methods should be able to simulate equilibrium between energy supply and demand, and the demand for goods and services provided by energy (direct structural change).**
3. **The Canadian economy is highly trade dependent and the methods should be able to simulate export and import substitution effects (direct structural change).**

All the comments for criteria 1 apply for criteria 2 & 3. In early designs of CIMS, it was postulated that the demand for goods and services would have to be split into their export and domestic components, and that each would have to be dealt with separately. However, the Armington price elasticity includes domestic and foreign demand for a given country's products, effectively by measuring how much market share is lost to or gained from competitors.

A key issue related to the flow of goods and services is the degree to which the inputs and outputs of different sub-models are related. If they are, there is an argument for directly linking them. CGE models link sectors by using a table that relates the inputs and outputs of the various sectors. In the design phase of creating CIMS I conducted an intensive analysis of all possible cross substitution between products and services of the sub-models (one may think of this as looking for the linkages in a CGE's model's input-output table). This involved some literature review. Consistent in the literature was a concern for substitution of modes of travel in transportation, which was already included in the transportation model. It was found most end products in CIMS could be looked at as goods with international markets, whose demand would be governed by cost and the propensity to substitute imports for domestic production, or to save more or work less. In other words, their demand was not closely tied to that for other goods in CIMS.[46] The exceptions were the residential, commercial and freight transportation sectors. Households provide labour and financial capital inputs to the various sectors, and this returns from the productive sectors as disposable income to the consumer, while commercial and freight activity are intimately linked as secondary activity to manufacturing. These dynamics were accommodated by driving activity in the commercial, residential and freight transportation sectors by changes in value-added in the manufacturing sectors.

A significant characteristic about CIMS' linkage of residential, commercial and freight transportation demand with manufacturing activity is that it is one-way. Demand adjustment induced by lower or higher activity in manufacturing may lower or raise the costs of residential and commercial activity, which may in turn have feedback effects. For example, suppose housing costs have a rising marginal cost curve (incremental units cost more). If manufacturing activity falls due to a GHG tax, disposable income will fall, thus lowering residential activity. However, the marginal cost per unit of housing expenditures is also falling, which will induce some return of expenditure. This may be thought of as a reverse

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[46] Two significant linkages were noted. These were the flow of iron ore to the iron and steel industry from iron mining and the use of chlor-alkali and sodium chlorate as bleaching agents in the pulp and paper industry. Another possible linkage that emerged later was the link between metal smelting and mining.

rebound effect. The key issue is the slope of the supply curve for residential expenditures. It may be reasonably argued, however, that the residential construction and refurbishment industries are well developed and large industries whose technological base isn't developing rapidly, suggesting a flat long-run average cost curve.

In terms of outputs related to changes in demand, the sub-models were not initially designed to produce standard economic outputs such as welfare costs or value-added. A welfare cost equivalent was derived by mixing a measure of risk and option value with the financial cost produced by the model, while value-added is calculated by mixing statistical data with the financial data produced by the model. Both these calculations involve somewhat complicated post-run exercises.

Some challenges were encountered in the energy trade component of CIMS, related to how costs are depicted in the natural gas and crude oil extraction models. These models are not full depictions of technology use in those sectors, but instead are limited to the actions available to reduce greenhouse gas emissions. This made the calculation of the total cost of production problematic, and additional estimates were necessary to produce these full responses. For this reason the full dynamics in these two sectors are not included in the main AEEI and ESUB results of this thesis. Their effects are shown in the cost curves exercise that compares the effects of the various feedbacks. If the natural gas and crude oil extraction models are to be used for full endogenous pricing, such as is done for electricity, petroleum refining and end-use goods and services, a significant amount of work is required to improve the depiction of both the technologies and their costs.

4. **The methods should be able to simulate and track investment and capital formation (direct structural change)**
5. **The methods should be able to simulate savings, labour market, and disposable income effects (indirect structural change).**

CIMS' coverage of capital formation may be considered adequate for physical capital formation affected by an energy policy, but it does not cover all capital formation. Specifically, it misses the component whereby households, firms, and the government increase and draw down their financial capital, and thus increase (or decrease) the domestic financial capital stock available for future physical investment and consumption. In a closed economy, this would be very important, as the price of capital would be dependent on domestic supply and demand. In CIMS, however, the cost of capital is assumed to be determined on world markets and an infinite amount is available at the market price.

CIMS includes some disposable income effects, specifically those in the commercial and residential sectors from energy policy that affects the manufacturing side of the economy. Long-term disposable income, however, is also related to long-term savings and investment, and CIMS does not consider this aspect of the disposable income equation.

CIMS does not directly calculate labour market and government taxation effects. These can be estimated, if desired, from simulation results. In this sense, I cannot completely test the relative importance of direct and indirect structural change effects. To do this, CIMS would have to incorporate or be linked to a macroeconomic model that accounts for capital and labour formation over time, as well as government tax recycling. This area of potential research will be addressed in the next chapter.

In summary, CIMS simulates almost all the direct and most of the indirect structural change effects engendered by an energy policy. The importance of the missing indirect structural change effects is a question for further inquiry.

6. **The methods should allow a wide range of scenarios, including testing of alternative assumptions (e.g., Canada as a price taker for the cost of capital, the ongoing dominance of US trade for Canada, full flexibility in the turning on and off of individual portions of the feedback systems).**

If all its capabilities were demanded simultaneously, CIMS' scenario limits are *currently* as follows (these limits could be broadened at need):

- CIMS assumes Canada is a price taker for capital, i.e., investment demand and savings supply has no effect on domestic interest rates.
- The macroeconomic elasticities assume a relative, not absolute, price shift with Canada's trading partners, i.e. their cost of production for a given good or service remains the same while Canada's rises. This can lead to some relative pricing issues. For example, what if Canada and its trading partners had climate change policies involving GHG pricing, and their costs of GHG reductions were different? What if their costs of production were different? Finally, what if market mechanisms to transfer GHG reductions were unavailable and the marginal prices for GHG reductions were thus different? If the relative prices in all three questions were known, the elasticities could be modified to reflect the differences. In the first and second cases, the ratio of the relative supply schedules could be

used to multiply the elasticity – if Canada's net cost of supply schedule (supply curve) for a given industry were twice that for the US, the elasticity would be doubled. If the marginal prices were different, and Canada's cost of carbon were \$50 / tonne CO_2e, while that for the United States was \$25 / tonne CO_2e, and both had the same long term supply schedule (the same technologies), the elasticities could be cut in half. The current demand system has the advantage of accommodating all of Canada's trading partners using parameters measured from historic data, but in the future it may be useful to add sub-models to represent the US, Asia and possibly Europe to simulate the potential dynamic trade shifts.

- Electricity trade is mostly all north-south between Canada's regions and the United States in the model. This is primarily because we have had historic surpluses in the provinces with large amounts of hydroelectricity, and it has been more profitable to sell electricity to the United States rather than to neighbouring provinces. There is the possibility Canada could choose to trade its electricity East-West to accommodate a goal related to energy policy. It would likely be a medium sized project to incorporate inter-provincial trade in electricity in CIMS.

CIMS as it is currently structured is well suited to analyzing the demand and disposable income effects of an energy policy. It does not, at present, have the capability to assess long-term taxation, capital formation, and capital account effects. Should these capabilities be desired, linkage with an established macro model or further development of the macro functions in CIMS is required. As a final point, given the uncertain nature of the world trading climate, estimated trade elasticities may be uninformative, and the user may be required to use "guesstimated" values. This is a fundamentally different issue, however, from the use of guesstimated values for production functions.

7. **The macro-economic equilibrium of the model should not depend on commercial models for which access would be expensive and restricted.**

No other models were linked with CIMS, eliminating issues with this criterion.

8. **Data requirements of the model should mostly be limited to regularly available data sources or data that can be estimated from relatively modest surveys.**

Almost all the data required to turn the sub-models into CIMS were acquired from ongoing Statistics Canada sources, and have been regularly updated. The only exception is the body of Armington price elasticities, which were acquired from a one-time study commissioned for Finance Canada. The elasticities were calculated from 30 years of data, however, and are unlikely to require revision in the near future. Should recalculation be required the method and data sources are well documented.

9. **The design of the model should be as simple, maintainable, and flexible as possible given all its other requirements.**

This criterion is related to the last, except it also includes the long-term viability of the structure of the model. CIMS has passed through two complete programming versions since it was first constructed, and is now undergoing a third. The first was more flexible than the second, but the interface was difficult to use. This is partly because it utilized only two programs in two languages (APL for all sub-model function and the feedback dynamics, and Microsoft EXCEL/ACCESS for data strictly related to the feedback systems). The second had a user-friendlier interface, but was more rigid because it involved the interplay of four different programs in four different languages (APL, Excel/Access, Visual Basic and C++). A third version is currently being developed, whose engine is still APL but all other interface and data storage function is in Java. This version should be more flexible and enduring.

10. The design of the model should accommodate the underlying ISTUM sub-models, which have seen 15 years of development.

In some respects, the sub-models set the structure of the integration framework. Each of the sub-models, while simple in its dynamics, is a complex and data intensive structure. The sub-models also set the boundaries between the technology simulations for the macroeconomic feedbacks. Much standard CGE methodology did not apply. For example, a key agent in CGE models is the "household" or "consumer", who earns wages while providing labour, consumption, and savings. In CIMS, the consumer is separately found purchasing goods and services, in a house, at the wheel of a car, and in commercial and institutional buildings. CIMS' consumer does not exist in one place, as compared to their counterpart in a standard CGE model, where utility, income, and purchasing characteristics may be closely coordinated. The use of the Armington elasticities, which are measured at point of purchase and thus represent total domestic and foreign consumer utility for the good in question, take care of this issue to some degree.

5.2 AEEI and ESUB results

The parameterization experiments were designed to test what AEEI and ESUB estimates would emerge from a behaviourally realistic technology simulation model with and without structural change feedbacks. It was initially guessed that the estimates could differ depending on whether or not structural change feedbacks were included.

First, there are significant differences between the AEEI and ESUB parameter estimates for the various sectors. This suggests that sectoral disaggregation is important if there is a divergence of views on the structural evolution of the economy. If sectors with high ESUB values grow more quickly, then the responsiveness of the economy to price-based policies will increase. This reasoning suggests that the AEEI and ESUB estimates are sensitive to structural change, and that national aggregate estimates will change in a world where the policy modifies the overall structure of the economy.

Second, with minor exceptions, the inclusion of structural change feedbacks did not directly affect the AEEI estimates and affected the ESUB estimates for only a couple of sectors with high elasticities of demand and significant energy consumption (pulp and paper and iron and steel production had their K for E elasticities adjusted from 0.02 to 0.1 and from 0.1 to 0.31 respectively). Other sectors, notably cement industry production which declines under any GHG pricing due to unavoidable process emissions, met both these conditions but structural change had very little effect on its K for E ESUB. This lack of a structural effect on the sector estimates, as opposed to the national aggregates, suggests several things. In terms of the AEEI, the long-run sector estimates for 2030 are not sensitive to structural change feedbacks because the characteristics of the technology stock would be the same with both smaller and larger production. In terms of the ESUBs, the sector estimates may not be sensitive to the range of energy prices tested. The maximum energy price increase was 75% and the maximum decrease was 50%. A GHG policy with prices from \$10-\$150 / tonne CO_2e has the potential to increase the effective price of natural gas by 16%-235%, gasoline 7%-105%, and coal 45%- 675%, depending on the starting prices (\$3, \$10 and \$2 / GJ respectively for this explanatory exercise). This is why the structural change feedbacks have a much larger effect on the cost curve estimates, whose GHG price changes induce larger price changes, than on the AEEI and ESUB estimates.

Another result was the diagnostic utility of the AEEI and ESUB measurements. Before conducting the experiments, expectations were formed of sector parameter values from both intuition and the economic literature. Where the estimates diverge from this literature and intuitive expectations, the question is whether the values from CIMS are more accurate. The most obvious divergence is in the transportation sector, whose low AEEI K for E substitutability (0.08) suggests that the behavioural parameters used to choose technologies might be overly resistant to change, or that technological development is stifled. Another measurement that seems curious but is explainable is the low K for E ESUB for Other Manufacturing (0.01). In this sector the use of energy is all in plug load, auxiliary equipment, lighting, heating and cooling and electric motors to drive pumps, compressors, conveyor belts, drills, etc. This suggests that these energy uses have very little potential for capital for energy substitution that raises energy efficiency. This may be partly explained by the very high behavioural discount rates used for choosing auxiliary equipment; these are typically 50% to reflect the desire for a 2 year pay-back on the investment (Nyboer 1997). Inter-fuel substitutability in this sector is quite high, however, specifically that between electricity and natural gas for heating water.

An interesting observation that emerges from the translog estimation process is the phenomena that there is no single elasticity estimate for a given input relationship – it changes with the input mixes. Standard practice is to report a mean value of the estimates (Nicholson 1992). These changes are significant in some cases, calling into question the use of constant elasticity of substitution equations. McKitrick (1998) openly questions the use of constant elasticity equations with guesstimated parameters and advocates the use of estimated generalized equations. Unlike CES models, CIMS allows for a changing elasticity relationship between inputs. In choosing between technologies instead of inputs within a fixed equation, the "production function relationship" is allowed to transform at will in accordance with the available technologies. Measurement of the potential importance of this advantage is a possible area for further research.

One potential application of this research is to use CIMS as an alternative means of estimating the key parameters in a CGE model. Most of the models use "guesstimated" values, with a minority using parameter estimates established from regression of historic data. The latter are definitely an improvement on the former, but they are still open to the critique over whether past data from a world with no climate change policy and different energy needs can provide us with valid data for a world where GHG emissions have a tangible cost and liquid fossil fuels have become scarcer. These research results provide a method for estimating parameters under these conditions, as well as a set of alternate parameter estimates that reflect possible future technology sets.

5.3 Using CIMS to improve information for policy makers: Cost curves of emission reduction for Canada

Three separate cost curves analyses were presented: 1) an analysis of the relative importance of the four levels of feedbacks, 2) a separation of the effects of GHG intensity and direct and indirect structural change adjustments on GHG emission reductions, and 3) two full scale cost curves exercises.

5.3.1 Cost curves of abatement under four levels of feedbacks

The comparative feedback exercise produced a few counter-intuitive results. First was the effect of adding basic energy supply and demand integration, which reduced GHG reductions. This reflects the importance of electricity substitution to GHG emission reductions, and the effects this has on its price. Second were the effects of including energy trade. I found that changes in energy trade are responsive to several variables with high uncertainty in CIMS. These variables include the degree to which CIMS represents the total cost of production in the natural gas industry as well as how the export substitution elasticity may change given relatively large changes in the cost of production. To explore the specific uncertainties of energy trade, the elasticities were adjusted down 50% and the cost of production coverage figures were adjusted up and down 50%. The outcomes changed the emissions reduction by 10's of megatonnes of CO_2e at all prices, but the relative importance of energy trade versus the other feedbacks did not change. Despite these uncertainties, the simulation results from CIMS indicate energy trade may be highly responsive to GHG policy and significant to its outcome. Inclusion of structural change feedbacks also altered the simulation results substantially, indicating they should not be assumed away in future studies.

5.3.2 Separation of the effects of GHG intensity and the direct and indirect structural change feedbacks on GHG emission reductions

In the early stages of this research it became clear that while most researchers agreed that both technological change and economic supply and demand feedback dynamics mattered, how one modelled energy policy depended on which of the two one believed to be more important – very few had attempted to explicitly study the relative importance of these dynamics. The top-down modellers used simple technology dynamics while the bottom-up modelers used simple supply and demand dynamics, if at all. The results of this exercise do not attempt to solve this debate, but basic testing with the model indicates that while technological adjustments provide at least half to two-thirds of the initial response to GHG policy, direct and indirect structural change become more important with more aggressive policies. Because CIMS is missing tax recycling and government finance dynamics, results from CIMS are biased to underrate the effects of indirect structural change, suggesting that for a moderately strong policy technology adjustment (changes in GHG intensity) and economic feedbacks might be equally as important. This bears exploration, as the dynamics of technology and preference development are currently being improved in CIMS, and there is speculation of an experimental linkage with a CGE model.

5.3.3 Results of two full scale cost curves exercises

The results of the two full-scale cost curves exercises were presented to show how costing of GHG emissions reductions was approached in policy analysis with CIMS, how actions that provided the emissions reductions were defined and, finally, how one might include emissions reduction actions exogenous to CIMS. These two studies brought forward many topics that were not considered in the initial design of CIMS, and added to its richness. These topics include:

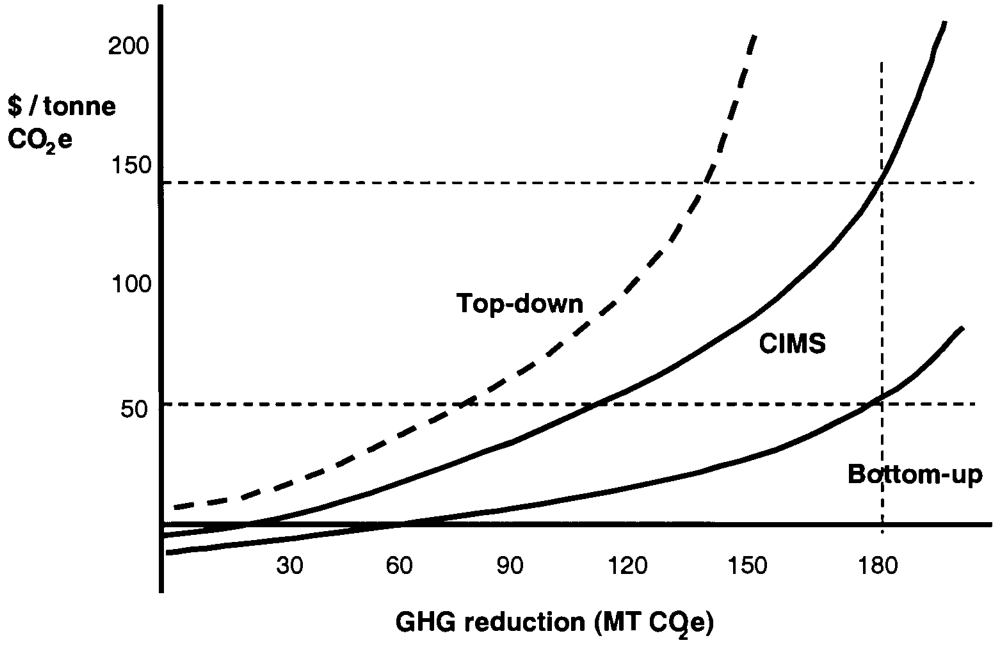
- An in-depth study of how the portrayal of capital investment in CIMS compares to its portrayal in the national income and costing accounts.
- Clarification and homogenization of CIMS' costing concepts with those normally used in the economics literature, such as "welfare cost" and "value-added."
- Sharing of the risk component of welfare costs amongst energy supply sectors when energy supply and demand integration is incorporated.
- The costing and modelling of inter-modal substitution in transportation.

Perhaps the most important characteristic of these two studies was the translation of the outputs that come from CIMS into results understandable and usable by policymakers.

5.3.4 A comparison of CIMS' costs curves to those for bottom-up and top-down models

Figure 14 provides a comparison of cost curves for 2010 that emerge from CIMS, a bottom-up, and a top-down model, for GHG prices imposed from 2000 onward.

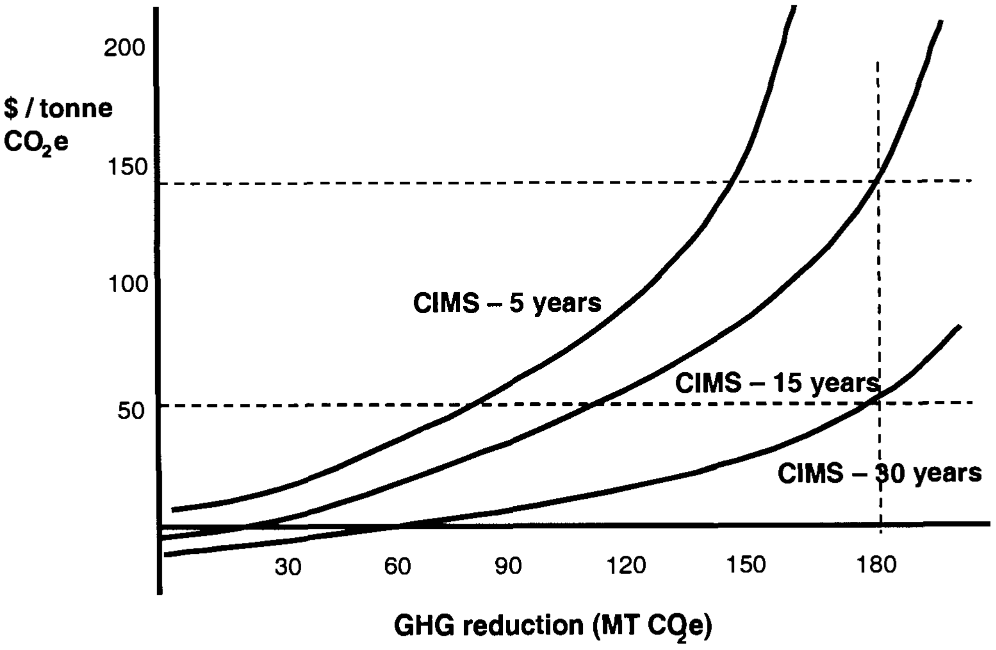
Figure 14 Canadian GHG emissions reduction cost curve (2010)



GHG reductions cost the most under the top-down estimate, and least under that for the bottom-up, with CIMS being somewhere in between but closer to the top-down estimate in the 10-year time frame. The bottom-up (MARKAL) and CIMS cost curves were generated using the same financial costs and other characteristics of technological options, an identical macro-economic forecast, and the same macro-economic model, TIM/RIM, to simulate feedbacks (Jaccard *et al.* 2003a). Firms and households in MARKAL used the social discount rate to compute financial costs, used the same financial costs to compete technologies, and employed perfect information across time and space. CIMS' firms and households, by contrast, use behavioural discount rates and intangibles when calculating costs. MARKAL's bottom-up permit price to achieve the Kyoto target is about $50 / t CO_2e, and the total cost is $15 billion compared to the CIMS estimate of $70 billion. The top-down curve is an aggregate estimate from the literature, which generally shows asymptotic curves once input normal substitution is exhausted, unless a back-stop technology (or "safety valve") is incorporate.

While CIMS is behaviourally realistic like top-down models and technologically detailed like bottom-up models, technological change takes time to occur, the amount of time necessary for the existing capital stock to be replaced entirely, and for new, technologically feasible equipment to be developed. This means that CIMS' cost curve will be closer to top-down when the time allowed for policy to act is short, and closer to bottom-up when more time is allowed. Figure 15 provides approximations of this time dynamic.

Figure 15 CIMS GHG emissions reduction cost curves for 5, 15 and 30 years



An alternative comparison is between the CIMS results and those of the US government's NEMS model, a hybrid like CIMS that is technologically explicit, behaviourally realistic and includes macro-economic feedbacks. In an application of NEMS to estimate the impacts of the US Kyoto commitment, a carbon tax (or permit price) of $294 USD / tonne of carbon was required to reduce emissions in 2010 to 3% below their 1990 levels (US Energy Information Administration, 1998). The 3% reduction is most directly comparable to Canada's Kyoto target, because at these targets both studies exclude the effect of forestry and agricultural sinks. When the US carbon tax is converted to Canadian currency and from carbon to CO_2e, it equals about $125 CDN / t CO_2e. While the costs for the two countries are similar, the CIMS estimate for Canada is slightly higher at $150 / t CO_2e. One important distinction between the two countries – this may explain the modest cost difference – is that the significant role of coal in the US electricity system offers lower cost opportunities for emission reduction relative to Canada, whose electricity system is more than 50% provided by hydropower.

5.4 Uncertainty in CIMS

"All models are wrong; some are useful" – attributed to George Box

The purpose of models may be argued at length, but their inaccuracy is a fact that cannot be ignored. Purists may argue that they may only be used for learning purposes, but more practical critics point out that decision makers are often faced with using information inaccurate in details but more or less accurate in direction, or none at all.

How uncertain are the ESUB and AEEI parameters and the cost curves results estimated using CIMS? For the ESUB and AEEI results these uncertainties divide into two parts: 1) how well the translog production function duplicates the variation in the pseudo data, and 2) the quality of the data and dynamics in the CIMS model which produced the pseudo data, specifically the representation of future technologies and household and firm behaviour. Only the latter uncertainty applies to the cost curves results. The first source of uncertainty is a modest issue about the translation of CIMS' dynamics into statistical parameters, and can be assessed with standard statistical indicators. Partly as a byproduct of the process, the coefficients of determination (adjusted R^2) are generally very high (all >65% and usually >85%), and the coefficients on the independent variables are highly significant. These details are available on request and are included in CD-ROM Appendix H.

The second source of uncertainty is much more challenging and is pervasive throughout the overall structure of CIMS – the accuracy of its data and its structure. There are several levels to CIMS, each with its own sources of uncertainty. How accurate are the techno-economic data and behavioural parameters at the sub-model technology competition level? How accurate and representative are the nodal structure and dynamics of the sub-models and the competition behaviour parameters that apply at this level? How accurate and representative are the data and behavioural parameters pertaining to the energy and final demand flow and price feedbacks? These issues are largely addressed in the sections on building the model, but deserve some repetition here. Table 36 provides a list of CIMS' data & behavioural parameters for the technology competitions, sector structure, and structural change feedbacks.

Table 36 List of CIMS' data & parameters

Technology competition data & parameters	**Sector structure data & parameters**	**Structural change feedbacks data & parameters**
Data		
The set of technologies portrayed	Initial output forecast	Cost of production coverage values
Capital cost by technology	Initial energy and emissions forecast	Calibration values for energy supply and demand
Fuel use by technology	Exogenous emissions by sector	Financial cost of capital used for pricing
Emission by fuel and technology	Structural relationships between intermediate and final demand technologies	
Behavioural parameters		
Intangible costs by technology	Mode choice intangible costs in transportation	Armington price elasticities
Declining capital cost rate of decline and asymptote. Currently being transitioned to a function based on cumulative production.	Process choice intangible costs in industry (mechanical vs. chemical pulping, basic oxygen vs. electric arc furnaces, boilers vs. cogeneration).	Relationship between industrial value-added and freight transportation and residential and commercial building activity
Discount rates by technology		Savings vs. consumption elasticity
Variance parameter by competition		Work vs. leisure elasticity

5.4.1 Technology and equipment stock data in CIMS

It should be noted that the dynamics that allowed me to use CIMS to estimate the AEEI and ESUB parameters are the *turnover of capital stock and the substitutability of the capital stock for energy inputs.* In a very fundamental way, these parameter estimates are dependent on the quality of the technology data in CIMS.

The source of these data, the technology cost, fuel use, and emissions characteristics, are key to any results from CIMS. CIMS was developed within the Energy and Materials Research Group (EMRG) of the School Resource and Environmental Management at Simon Fraser University. EMRG is closely associated with the Canadian Industrial Energy End Use Data Analysis Centre (CIEEDAC), an independent data analysis agency funded primarily by Natural Resources Canada. Much of CIMS' data was collected initially for CIEEDAC, which reviews its data annually in collaboration with the Natural Resources Canada, Statistics Canada and industry associations. There are similar Canadian agencies for transportation, residences, and commerce, and much of the data for these models came from these agencies, the US Department of Energy, other government agencies, and industry publications. Occasionally a "guesstimate" value must be used, usually by using the parameters for a similar process or technology. This practice, which introduces more uncertainty, was limited as much as possible.

5.4.2 Sub-model technology competition parameters

The algorithms used to compete technologies are based on life-cycle-cost calculations, with intangible costs added and subtracted to reflect behaviour. These intangible costs are the key source of uncertainty at this level. Where possible they have come from the empirical literature, but these are not commonly calculated values. Normal practice until recently has been to compare model simulations with historical technology evolution and to ask industry experts to verify the realism of experimental model results (Jaccard and Roop 1990, Jaccard *et al.* 1996, Jaccard *et al.* 2003b, Nyboer 1997).

Over the last three years, EMRG has made an effort to empirically estimate the key discount rate, intangible cost and variance parameters using discrete choice analysis. Studies have been completed for personal transportation (Horne 2003), thermal technologies in industry (Rivers 2003), and residential energy use choices (Sadler 2003). Studies are in progress to assess the behavioural parameters associated with evolutionary technologies, such as the electric hybrid vehicle, and revolutionary technologies, such as the hydrogen fuel cell vehicle. This research program should improve the assessment of uncertainty associated with the technology choice behavioural parameters.

5.4.3 Sub-model structure and output data and node competition behavioural parameters

The flow models are structured as interconnected nodes, with intermediate products feeding final output. These final outputs are exogenous forecasts taken from Natural Resources Canada, and are accompanied by energy consumption and emission forecasts to which CIMS is calibrated. Some of the intermediate products and services compete, such as personal vehicles versus public transit in transportation, boiler versus cogeneration in industry and chemical versus mechanical pulping in pulp and paper production. All these competitions incorporate financial and intangible costs, in much the same manner as technology competitions.

While sector experts have reviewed most of the flow models, there is ongoing work in the energy processing and upstream sectors (petroleum refining, natural gas and crude oil extraction). These sectors can be viewed as having more uncertainty attached to them compared to the others. The key node competitions are also being re-estimated in part to reflect the results of the discrete choice analysis research. Another sector whose flow model may change is Other Manufacturing. It is comprised of industries with high value-added and low energy use, and the recent emphasis on financial costs, prompted by this project, has highlighted the necessity of revisiting this sub-model in order to improve the technology competition, flow model and demand dynamics for individual goods.[47]

5.4.4 Energy flow and direct and indirect structural change algorithms and behavioural parameters

The equations used in CIMS to adjust demand and equilibrate prices and markets for both energy and final goods and services have been developed and tested over the last five years, including proofing during three large federal Canadian climate change costing analyses (Bataille *et al.* 2002, Laurin *et al.* 2003, MKJA/EMRG 2000). The basic algorithms are functionally the same as those in a CGE model.

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[47] Other Manufacturing includes: 1) Food, Tobacco and Beverages, 2) Rubber and Plastics Products, 3) Leather, Textiles and Clothing, 4) Wood Products, 5) Furniture, Printing and Machinery, 6) Transportation Equipment and 7) Electrical and electronic equipment.

The parameters and data for the energy and goods and services structural change feedbacks come from two key sources as well as a small sample of literature. The two main sources are annual Statistics Canada publications and T. Wirjanto's study of Armington price import substitution elasticities, which were estimated from historical data. The Statistics Canada data were used to set structural values, such as the capital coverage parameters and may be regarded as high quality data.

For the energy flow and trade algorithms, the key sources of uncertainty are the calibration values used to make the Policy and BAU runs match. The calibration values are dependent on the quality of the initial demand and technology data entered into the sub-models.

The behavioural algorithms for energy and goods and services pricing are sensitive to the capital coverage values for CIMS, which are calculated by comparing CIMS' data with that from Statistics Canada, and the substitution elasticities. Statistics Canada values were unavailable to accurately calculate to what degree CIMS covers the cost of producing crude oil and natural gas and it is uncertain how the export elasticities may change once the price of natural gas and oil changes by large relative amounts. The parameters of the energy trade function are probably the least certain of all the structural change feedback linkages.

5.5 Discussion summary

This chapter had four sections. The first discussed how well I met my design and construction criteria in creating CIMS from ISTUM. The second was an analysis of the AEEI and ESUB estimation and cost curves results. The third section addressed the effort to separate the effects of GHG intensity changes and direct and indirect effects under GHG policy as well as the cost curves results. The chapter finished with a discussion of uncertainty in the results of the CIMS model.

CIMS goes a long way to transforming ISTUM from an independent set of sector sub-models into a general equilibrium model, but is still only partial equilibrium in that it does not capture changes in domestic consumption, savings, wages and interest rates. The feedbacks that are included, however, especially the energy and demand adjustment systems, turned out to have significantly changed the GHG abatement and cost results of the model when policies are applied. These dynamics did not, however, affect the AEEI and ESUB parameter estimations. These latter estimates differed greatly by sector. The AEEI were in the range suggested by the literature, but the ESUB estimates tended to be lower. Significantly, the ESUB estimates change with input cost shares, which suggests the use of constant elasticity of substitution equations may be flawed.

The results of the experiment to differentiate the effects of GHG intensity changes and direct and indirect structural change show that technical adjustments make up about half the response to simulated energy policy, and macroeconomic demand adjustments the other half. Technical adjustments predominate with minor policies, while the importance of macroeconomic demand adjustment increases with the strength of the policy. The cost curves of GHG abatement provide estimates of what GHG reduction can be expected from the Canadian economy with various tax levels, and show what actions generate these reductions.

In assessing the uncertainty in these results from CIMS, whether they be the AEEI and ESUB parameter estimates or the cost curves of GHG abatement, one needs to differentiate at what level one is looking at. At the sub-model level the greatest uncertainty is associated with the technology sets and their constituent parameters. Are they sufficient? Do they accurately reflect the real world? At the structural change level the greatest uncertainty is that associated with the energy trade mechanisms.

6 Conclusions & Future Research

In this final chapter I revisit the key conclusions of this thesis, review some research underway that has relevance to this work, and propose future research possibilities.

6.1 Key conclusions from this project

The elasticities and AEEI for individual sectors differ. According to the data and parameters in CIMS, ESUB and AEEI differ from one sector to the other. This suggests that aggregate models with single economy values for these parameters may be unhelpful to policy-makers seeking to explore the effects of policy induced structural evolution within the economy.

The energy supply and demand integration, energy trade, direct and indirect structural feedbacks, while they do not seem to have much of an effect on CIMS' inherent AEEI and ESUB, have a large effect on GHG emissions reductions and hence the cost of achieving energy and emission reductions goals. Studies that show response to policy without demand feedbacks or that focus on the demand feedbacks of only one market instead of the collected effect of demand feedbacks on all relevant markets, could miss some important dynamics. All other things being equal, the order of importance of the above list of dynamics in CIMS, from least to most, is as follows: indirect structural changes in disposable income, energy supply and demand integration, energy trade and finally, direct structural changes in goods and services demand. Both direct and indirect structural change matter progressively more as the strength of the policy increases.

The ESUB experiments showed that the elasticities change appreciably with input cost shares in CIMS. Constant elasticity of substitution equations, such as those used in the majority of CGE models, may be inadequate for accurately portraying a sector's production function. Generalized functions, such as the translog or normalized Leontief, while more difficult to estimate, may provide results that are more accurate and, as a bonus, overcome the calibration criticism of many CGE models.

6.2 Future research

Several possible projects have been identified in the course of this thesis. Future research with CIMS divides into three main categories: addressing already identified challenges, adding new capabilities to existing functions, and exploring wholly new areas. The AEEI and ESUB results and their utility as a diagnostic will be used as a focus for the discussion.

6.2.1 Validating and exploring the AEEI and ESUB parameter results from the sub-models

A common result for most sectors was that inter-fuel substitution appeared to be more significant than efficiency as a response to increased energy and emissions costs. The national capital for energy substitution elasticity value is 0.27, while the electricity for natural gas and natural gas for oil product cross elasticities are

1.91 and 1.73 respectively. Most of the latter substitutability, however, is in the commercial (2.66 (Elec. for NG) & 2.11 (NG for Oil)) and residential (2.98 (Elec. for NG) & 2.99 (NG for Oil)) sectors, with the value for most industrial sectors being in the 0.05 to 0.65 range. Some review of inter-fuel substitution in the commercial and residential sectors is advisable.

The natural gas and crude oil extraction and transmission models require some improvement, which has already begun at EMRG. A thorough review of their technology capital costs is necessary, as unexpected cost numbers emerged from crude oil extraction during runs. A key reason for addressing natural gas' cost of production is the desire to experiment with setting its price endogenously within the model.

More generally, there may be a requirement for changing the energy supply and demand integration system so that the energy demands of the energy supply sectors are completely endogenous. At present petroleum refining's demand for electricity, and upstream oil and gas extraction and coal mining's demands for all energy goods, are exogenous. There are several possible methods of making energy demand amongst the energy supply sectors fully endogenous, but the best option identified at present is to use some form of limited linear programming equilibration of the energy supply sectors after the demand sectors have run.

Finally, in its present form, the transportation model is unresponsive to energy price changes, mainly because standard gasoline vehicles have a significant advantage over alternative fuels and technologies. In addition, consumers seem to strongly prefer traveling in single occupancy vehicles to all other modes of urban travel; for example, transit has an annual relative intangible cost of +$12,000 compared to single occupancy vehicles, while this intangible is +$6,000 for high occupancy vehicles (carpooling). A new high efficiency gasoline vehicle, on the other hand, costs only $17,000. Even if transit were made free, there would still be an annual intangible cost of about $11,000 between single occupancy personal vehicles and transit. These preference parameters were estimated from the NEMS transportation model. If they are accurate, perhaps the most effective policy means of reducing GHG and criteria air contaminant emissions will be to change the emissions profile and technology of personal vehicles. Here, however, we meet relative cost issues – in CIMS most alternative fuel and technology vehicles cost upward of $10,000 more than their gasoline equivalents. If policy speeded up the commercialization of new technology the costs may fall, and consumers might become more amenable to accepting them. CIMS in its present form does not capture these dynamics well; hence, EMRG's current research program to improve the technology development dynamics in the model.

6.2.2 EMRG's technology development research program

How might ESUB and AEEI change given that technologies with lower GHG emissions might become less expensive once sufficient numbers of them have been produced (*technological change*)? How might behavioural parameters change once the perceived risk of newer energy or GHG emission reducing technologies falls with market penetration (*preference shifting*)? In order to answer these questions adequately, some changes are required to CIMS' technology competition algorithm.

Several researchers at EMRG, including the author, are engaged in a research program to improve depiction of technological development in the CIMS submodels. This currently includes three key changes to the technology competition algorithm. The first is to change the declining capital cost function from being based on market share to being based on cumulative production. The general function is described in Equation 21.[48]

$$CC(t) = CC(0)\left(\frac{N(t)}{N(0)}\right)^{\log_2 PR} \qquad (21)$$

N(t) = current production
N(0) = production upon introduction to market
CC(t) = current capital cost
CC(0) = capital cost at time of introduction to market
PR = progress ratio, or the rate at which capital cost falls with each doubling of production

The declining intangible cost function is designed to show how consumer's intangible costs for a new technology will fall as that technology's market share increases. It is described in Equation 22.

$$I(t) = {}^{I(0)}\!\Big/_{(1+A^{(kNMS_{(t-1)})})} \qquad (22)$$

I(t) = current intangible cost
I(0) = initial intangible cost
A & k = constants that define the shape of the declining function

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[48] One commentator desired clarification if these declining costs were due to returns to scale, or via "neutral technical change". The answer is both – it is descriptive ratio that describes the net effect of all production related factors on the technology's cost.

NMS = new market share

In early testing with the new declining intangible and capital cost functions, it was found that with plausible parameter values and under moderate GHG taxes the capital cost of electric hybrid cars fell significantly as the number of units increased, which in turn decreased their intangible costs, which increased the number of units purchased, and so on. These changes were enough to take electric hybrids from having very little stock in 2030 in the "non-declining" case with no GHG taxes to 25-50% of the stock in 2030 with moderate taxes. Given the low ESUB and AEEI found for transportation in this study, these new functions may significantly change the AEEI and ESUB results for both transportation and Canada as a whole depending on assumptions about behaviour. Once the testing for the new functions is complete, a new set of AEEI and ESUB results will be calculated with a suite of different policies; these will be compared with those published in this thesis.

Another new technology competition function in the early stages of development is a "sunset" function, an algorithm that removes obsolete technologies from use and competition. For example, if a technology's market share were to fall from 50% in 2000 to 10% in 2015, it may be removed from use and competition in 2020. Once testing is completed with this algorithm, the AEEI and ESUB parameters will be recalculated to assess its effects.

6.2.3 The future of CIMS as an economic model

CIMS is a technology choice model, structured around energy flows, fitted into a framework of equilibrium feedbacks. These feedbacks turned out to be important for emissions reductions, especially for policies that significantly affect the cost of producing goods and services. If CIMS is to adequately assess policies to reduce emissions and affect technological development it needs to include all necessary equilibrium feedbacks, using either its own system for structural change or by linkage with a developed macro model. These feedbacks may be divided into direct structural change (demand and product substitution adjustments), and indirect structural change (disposable income, labour market, savings and investment, currency and government taxation effects). A discussion of CIMS's current ability to handle these feedbacks, and suggestions for improvement, are presented below.

Direct structural change (changes in demand for goods and services).

To include demand feedbacks one requires prices for goods and services. In the long-run with reasonably competitive markets, prices are determined by the cost of production.[49] CIMS is missing many costs, however, and is not always arranged according to end products with market prices. To accommodate the missing costs, I assumed that they did not change in response to policy and that they remained consistently proportional. The missing costs are composed

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[49] The cost of supplying an additional unit generally first falls and then remains static over a wide range of quantity for most goods; please earlier discussion.

primarily of capital not associated with consuming energy, materials and labour unrelated to physical capital.

A further complication is that there is an inconsistent treatment of end-use goods and services in CIMS' flow models. In most of the flow-models the end products are one level below an arbitrary grouping node (Other Manufacturing), while others have the end product at the top (Natural Gas). This was accommodated with special programming when applying the demand elasticities, but future development of the model would improve the consistency of this linkage.

Indirect structural change (disposable income, savings and investment, currency changes, labour market and government taxation adjustments). CIMS covers some disposable income effects as they relate to demand in the commercial and residential sectors, but does not cover savings and investment, labour market, exchange rate or government taxation responses. Moreover, the covered effects are asymmetric (one-way) – changes in manufacturing activity are reflected in freight, commercial and residential activity, but cost changes in these sectors do not affect their own demand. These disposable income effects on emissions reductions are negligible with low tax policies, but are more significant at higher taxes. The importance of the other uncovered indirect structural change feedbacks is uncertain, but again would depend on the magnitude of the tax policy.

Missing value-added. CIMS captures between a third and half of value-added in the economy. The missing elements include services, education, finance, retail and government expenditures on capital and labour outside of commercial buildings, the sectors where energy expenditures are negligible. When an energy policy is simulated in the existing sectors covered by CIMS, the indirect effects on the missing sectors are not accounted for, but could be significant depending on the severity of policy.

Labour & the missing service sector. I was unable to measure the substitutability of labour for capital and energy because it is included as a linear function of the cost of capital in CIMS. This method of including labour works in industries in which large amounts of physical capital must be used and most labour is directly related to this capital, but is inadequate in industries where labour forms a substantial portion of costs (services, finance, government, retail) and is more freely substitutable for capital and energy. In effect, CIMS is missing the fastest growing part of the economy – the service sector.

CIMS as it is currently structured simulates most direct structural change well and indirect structural change adequately, *as long as most of the policy incidence is in the energy intense sectors (manufacturing, transportation and energy supply).* If the policy incidence were outside the energy intense sectors, the disposable income feedbacks will be less comprehensive. In terms of CIMS' future development, how likely is it that CIMS will be required to model policies whose incidence will be outside the energy intense sectors, and should an effort be made to model the currently uncovered indirect structural change effects?

CIMS is an experiment in bridging the top-down bottom-up gap coming from the bottom. The underlying question it points to is not how important is technology, but how important is *indirect* or *secondary* structural change (the purview of dedicated macroeconomic models) to energy policy analysis? CIMS hints, *but does not confirm*, that it may be not nearly as important as technology and direct structural change. The next big experiment may be to measure how *returns* to sectors change under the influence of energy policy, while maintaining the technological explicitness of CIMS.

There are two paths to a more comprehensive macro-economic model that might deal with this question: developing CIMS further into a *bona fide* CGE model, and linking it to one that is already developed. Both paths have benefits and costs, and following both together may be beneficial. Linkage with an established CGE model would be easier if the goods and services produced in CIMS were defined in a consistent way, and the cost of producing these was clearly defined. The CGE model could provide for CIMS the missing indirect structural change effects, and CIMS could in turn provide a better picture of technological development.

The following projects would help improve CIMS as a CGE model and as a candidate for partnership with a developed macro model.

- *Costing:* Use accurate absolute (as opposed to relative) financial cost values for capital, labour, and energy, all in a single year's dollars.
- *Standardize the sub-models:* Put all final goods and services on the second level down in the flow model. Put all intermediate goods and services lower in the flow model, either as technology competitions or

exception nodes (services). This is important because policy may change the cost of intermediate goods, such as molten steel or pulp – with the current structure, their costs are not reflected in final goods such as slabs, blooms, and writing paper. This will also ease both using CIMS' own system of structural change feedbacks and linkage to other models – final (market) goods and services will all be defined in one place.

- *Make energy flows and pricing fully endogenous within the energy sector.* One suggested method has been to make this part of the model solve using a linear programming algorithm.
- *Change the elasticities so that they can adjust as demand changes, if estimates indicate this should occur (use a dynamic instead of static formulation)the.*
- *Add non-energy consuming capital and materials costs.*
- *Add a simple service sector.* This could be a simple CES production function, with capital and energy nested together and substituted against labour. This model would respond like the freight, commercial and residential sectors to manufacturing activity (i.e. via an input-output response table), with the added effect of labour substitution to replace capital and energy as they get more expensive. Alternatively, the commercial model could be expanded so that it is split, like Other Manufacturing, into finance, retail, hospitals, government/institutional, etc. A capital/energy vs. labour competition node would be added high up in the flow model.
- *Add a Construction & Renovation model*
- *Do sector financial product (value-added/GDP) as well as energy calibration.* Currently the base case is matched to historical energy data and forecasts. This could be done in comparison to forecasts of sector value-added as well.

- *Create a sub-model to represent trade with the United States, Asia, and maybe Europe.*

Linkage of CIMS with a standard CGE model could occur in one of two ways. Soft linkage involves a manual passing back and forth of variable values between CIMS and the candidate CGE model. Hard linkage would directly link CIMS and the CGE model within the same operating framework. The first method spares up-front programming and proofing labour, but would take more effort each time the linkage exercise was carried out. Hard linkage has larger upfront costs, but would permit many more linkage runs to be carried out afterwards. Both these methods have several drawbacks. First is the ongoing availability of a good CGE model. Some of the best models are proprietary, involving substantial funds for collaboration. Another challenge is the mapping of CIMS' sub-sectors to sectors in the CGE model. It is not simply a matter of matching CIMS' sector to those of the CGE model. Because of the way capital investment occurs in CIMS, CIMS captures only half of all economic activity, although it does not exclude any sectors.

A promising exercise would be to use CIMS to parameterize the sub-sectors of an already well-developed, highly disaggregated CGE model such as SGM or MIT-EPPA, using the techniques in this thesis to create AEEI and ESUB estimates. CIMS can estimate the parameters for a generalized production function (such as the translog or generalized Leontief), not just the single value used for constant elasticity of substitution production functions. Returning to the conclusions of McKitrick, an argument can be made CGE modelers should be using estimated, generalized functions in their models instead of calibrated, guesstimated constant elasticity of production functions.

6.3 Final words: Further exploration of the concept of physically realistic general equilibrium modelling

CIMS is not yet a full general equilibrium model, and may never be, but its shows the potential and challenges for a new genre of more “physically realistic” general equilibrium modelling. As computing power increases, software writing programs become easier to use, and more high quality government and industry technical and economic data becomes available online, it will become easier and easier to build models of this sort.

I pose the question – can technological general equilibrium models (TGEMS), or alternatively physical general equilibrium models (PGEMS), ever replace standard top-down models for general economic policy analysis? Will we ever be able to look into an economic model and see not just changes in the flow of money, but adjustments in the flow of physical, tangible things? It is almost 45 years since the essential theory of the CGE model was laid out by Debreu (1959), later turned into a functioning, usable and insightful system by Arrow and Hahn (1977). Given that this form of modelling has reached maturity only in the last decade and a half, it could be some time before physically realistic general equilibrium modelling catches on.

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Appendix A:
Use of the terms “option value” and “quasi-option value”

The “option value” referred to in this thesis is that extending from the financial decision making economics literature, stemming directly from Pindyck (1991), Dixit (1992) and Dixit and Pindyck (1994), and indirectly from Black and Scholes (1973) and Merton's (1973) seminal work in options pricing. In Dixit and Pindyck’s work “option value” is the value of additional information gained from delaying an investment decision as it pertains to that decision. As such, it is a value directly related to the characteristics of the decision – if there is no additional information to be had from delay, there is no “option value”. Dixit and Pindyck’s 1994 book contains a thorough review of the literature pertaining to financial decision making under uncertainty, and explains how real investment problems can be treated as option valuation problems.

“Option value” has had a different and somewhat more venerable meaning in the welfare and environmental economics literature. “Option value” in this context is the value of not exploiting or otherwise altering a “resource” on the premise that there may be some future value associated with its direct use in an unaltered state. The intuitive version of this argument was first presented by Weisbrod (1964). This idea has much intuitive power, but there were great difficulties in calculating this “potential future (non)-use” option value for practical cost-benefit analysis. From Weisbrod sprang two strands of literature, one which focused on the option price associated with risk aversion and another, more similar to the Dixit and Pindyck model and preceding it by almost a couple of decades, which focused on the value of information.

In the first strand of literature Cicchetti and Freeman (1971) formalized the concept in a welfare theoretical model where option value (OV) was the sum of expected consumer surplus (E(CS)) and option price for a decision, where option price (OP) was the sum of the agents' willingness to pay to preserve a resource for possible future use (OV= E(CS)+OP). This model was used thereafter as the base for all discussions in the welfare and environmental economics literature regarding this topic. Cichetti and Freeman's argument was that OV was usually positive. Schmalensee (1972) presented an argument that has stood until today that the sign on option value is ambiguous, with various authors showing that income uncertainty has a negative effect on option price, demand side uncertainty an ambiguous effect and supply side uncertainty a positive effect. The significant uncertainty surrounding this version of "non-use option value" has prompted Freeman (1993) to call for its abandonment in cost benefit analysis use. See Ready (1995) and Boardman *et al.* (1996) for a survey and summary of the literature.

In the second strand of literature springing from Weisbrod's intuitive option value, beginning with Arrow and Fisher (1974) and Henry (1974), there is instead a focus on the risk independent value of information to decisions. They specifically call the value of additional information gained from delaying an investment decision as it pertains to that decision "quasi–option value". In doing this they preceded Pindyck (1991) by 17 years. Arrow and Fisher's work is mentioned in Dixit and Pindyck (1994) in reference to decisions regarding environmental policy, but is not brought forward as part of the core history of the option value concept. Dixit (1992) makes no mention of Arrow and Fisher. Neither of Dixit's works seem to mention "quasi option-value". The mathematical models discussed by Arrow and Fisher and Dixit and Pindyck are at first glance different, but Fisher (2000) makes the argument that basic versions of their models are formally equivalent. His primary purpose was, in quote;

> (to provide) . . . license. . . (to). . . environmental and resource economists working in the Arrow and Fisher tradition to adapt results from the much more extensive body of work set out in Dixit and Pindyck, including the theory of call options in finance, which they show is in turn equivalent to their theory of investment under uncertainty.

In summary, it appears that Arrow, Fisher and Henry's "quasi-option value" and Dixt and Pindyck's "option value" emerged independently - this is my opinion only taken from a review of the literature above. The term "quasi-option value" continues to be used within the welfare and environmental economics literature, but the decline of Weisbrod's earlier "potential future use" concept of option value, and growth of Dixit and Pindyck's "option value" along with the financial literature, seems to have lead to the term "option value" gradually becoming synonymous with the more conceptually correct "quasi-option value". I use the former term due to its closer applicability to the making of capital investment decisions under uncertainty, and to its broader use.

Appendix B: Detailed results of the survey of climate change policy models

Starred (*) references are those referred to by the modellers, not references I quote directly. They are listed as footnotes instead of being included in the bibliography.

Pacific Northwest National Laboratories - The Second Generation Model (SGM)

General structure of SGM

SGM (Edmonds *et al.* 1991, Sands 2002, Sands and Schumacher 2003) is operated by Pacific Northwest National Laboratories. It is a collection of 13 CGE models that can be run independently or as combinations of regions trading carbon emissions rights. SGM operates in five-year time steps, from its 1990 base year through 2050. Capital stocks in SGM are grouped into five-year vintages, each corresponding to five years worth of investment. A production sector exists in SGM for each unique product. Each product has its own-price. For most of the SGM production sectors, a non-nested, single level constant elasticity of substitution (CES) production function exhibiting constant returns to scale represents the range of possible production methods; the relative prices determine the mix of inputs. In electricity and iron and steel the equivalent of Leontief production function is used to represent explicit individual generating and producing technologies – they are competed on a weighted lifecycle cost basis. Once capital is created it must remain with its original industry and until that vintage of capital is retired. Therefore an unanticipated price change, such as the introduction of carbon pricing, will not be fully effective until all capital stock in place before the price change has retired. This makes achieving short-term emissions targets expensive relative to longer-term targets.

Elasticities values in SGM

Elasticities in SGM are a mixture of empirically derived elasticities from translog models and generally accepted estimates from the Stanford Energy Modelling Forum (Sands 2002). Please see Table 37 for the producer and consumer elasticities in the SGM.

Table 37 Elasticity values in SGM

Activity (producers), consumption good (Consumers)	Long-run elasticity of substitution for producers	Short-run elasticity of substitution for producers	Own-price elasticity of demand for consumers	Income elasticity of demand for consumers
Agriculture	0.3	0.1	-0.38	0.32
Services	0.4	0.1	-1.02	1.01
Crude Oil	0.28	0.1	NA	NA
Natural Gas	0.28	0.1	NA	NA
Coal	0.28	0.1	-0.21	0.5
Coke	0.28	0.1	NA	NA
Electricity	0.1	0	-0.21	0.5
Refined Petroleum	0.1	0	-0.21	0.5
Distributed Gas	0.1	0	-0.21	0.5
Paper and Pulp	0.28	0.1	-1.02	1.01
Chemicals	0.28	0.1	-1.02	1.01
Non-metallic Minerals	0.28	0.1	-1.02	1.01
Primary Metals	0.28	0.1	-1.02	1.01
Food Processing	0.28	0.1	-1.02	1.01
Other Industry	0.28	0.1	-1.02	1.01
Passenger Transport	0.28	0.1	-1.02	1.01
Freight Transport	0.28	0.1	-1.02	1.01

AEEI in SGM

Input use in SGM, including energy, is calibrated over time to US government forecasts by adjusting input specific technical change parameters, or A(I/E)EI's.

Technological versus structural change in SGM

SGM distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

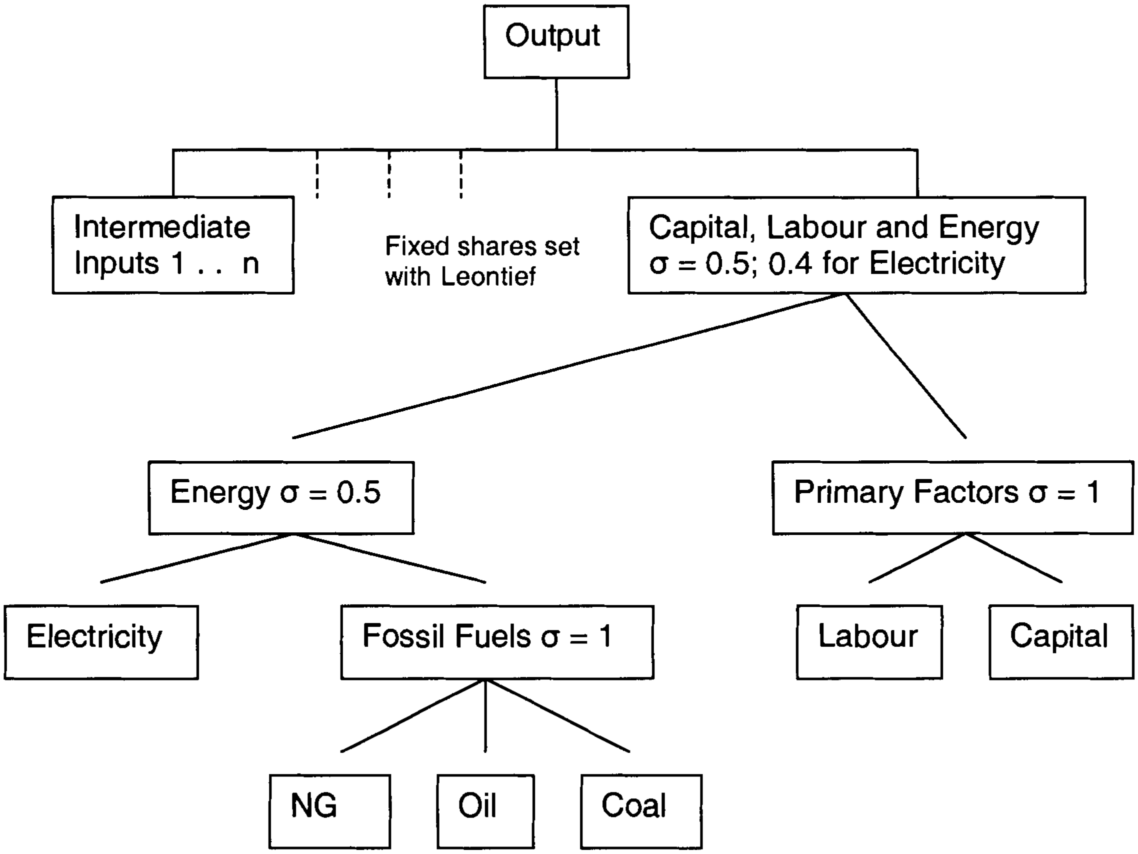
Massachusetts Institute of Technology Emissions Prediction and Policy Analysis Model (MIT-EPPA)

General Structure of MIT-EPPA

The Emissions Prediction and Policy Analysis model is a component of the Integrated Simulation Model (IGSM) of the MIT Joint Program on the Science and Policy of Global Change (Babiker *et al.* 2001). The model simulates the world economy through time with the objective of producing scenarios of greenhouse gases and their precursors, emitted as a result of human activity. These emissions scenarios are used as inputs into a coupled atmospheric chemistry climate model, including scenarios of natural emissions of GHGs from a Natural Emissions Model, to produce scenarios of climate change induced by GHGs. The model is also designed to evaluate the economic impacts of policies designed to limit GHG emissions. Research questions include the distribution of economic impacts across different countries, the effects of policies on compliance costs (such as with or without emissions trading or the participation of different groups of countries), or how other economic policies (such as limiting or subsidizing power choices, or adjusting taxes or subsidies on fossil fuels) affect the cost of GHG abatement. The model is often run “stand-alone”, without the full IGSM.

Production is represented by constant elasticity of substitution (CES) technologies that exhibit constant returns to scale. All models follow the basic structure in Figure 16. The model is primarily concerned with industry, manufacturing, and energy supply and purposefully ignores the complexities of the agriculture, material inputs and substitution of intermediate inputs.

Figure 16 MIT EPPA general production function map



Notable variations from the general plan include:

- The electric sector has the same structure as other sectors except at the very top node. Conventional electricity takes the place of domestic gross product and is substituted against nuclear electricity using a linear production function. The fossil fuels are further split out so that natural gas fired production is substituted against oil and coal at 1.0, while oil and coal are substituted against each other at 0.3. For nuclear energy, the nuclear resource is substituted against value-added at 0.04-0.4, depending on the elasticity of supply for the nuclear resource. Labour and capital are substituted at 0.5.
- The primary energy supply sectors have domestic product as the top node, which is built up from a non-fixed factor bundle and a fixed factor bundle with a CES using an elasticity of 0.6. The non-fixed factor bundle is built using a Leontief with intermediate inputs and a value-added factor.
- The oil-refining sector has domestic gross output as the top output node, with the primary factors, raw crude and intermediate inputs all brought together in a Leontief function. Labour and capital are substituted via a CES with an elasticity of 1.0.

Elasticity values in MIT-EPPA

All the elasticities reported above are long-run values, derived from Burniaux *et al.* (1992)*[50], Nainar (1989)*[51], Nguyen (1987)*[52], Pindyck (1979)*[53] and expert elicitation.

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[50] Burniaux, J.-M., G. Nicoletti and J. Olievira-Martins. (1992). "Green: A Global Model for Quantifying the Cost of Policies to Curb CO_2 Emissions". *OECD Economic Studies,* 19, 123-140.

[51] Nainar, S. (1989). "Bootstrapping for Consistent Standard Errors for Translog Price Elasticities". *Energy Economics,* 11, 319-322.

[52] Nguyen, H. (1987). "Energy Elasticities Under Divisia and Btu Aggregation". *Energy Economics,* 9, 210-214.

AEEI in MIT-EPPA

Following the approach first outlined in Edmonds and Reilly (1985)*[54], they specify an index of energy efficiency that grows over time, whose rate of increase is assumed to be equal to the rate of decline in energy use per unit output. They differentiate the growth of energy efficiency across regions and sectors according to the assumption that those industries responsible for producing primary energy commodities (coal, crude oil and natural gas) experienced no energy efficiency improvement. The energy input coefficients to the sectors therefore remain unchanged from their calibrated benchmark values. These are derived from base year social accounting matrices.

Within MIT-EPPA, representation of energy-saving technical change through the AEEI parameter is a way of directly forecasting, based on modellers' assumptions, the effects of innovation on the growth of the economy and its use of energy. The algebraic specifications of the regional trends in energy use are separate from other productivity trends. However, these trends are chosen by the modellers in constructing EPPA's baseline scenario to generate future trajectories of output, energy use, and emissions that all appear plausible in the light of history.

For all other sectors in each economy, energy efficiency is assumed to increase at an equal rate, which is region specific and varies over time. The initial rates of

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[53] Pindyck, R. (1979). "Inter-fuel Substitution and the Industrial Demand for Energy: An International Comparison". *Review of Economics and Statistics,* 61, 169-179.

[54] Edmonds, J. and J. Reilly. (1985). *Global Energy: Assessing the Future,* New York: Oxford University Press.

growth[55] were developed through a combination of expert elicitation and examination of historic rates of decline of countries' energy / GDP ratios (e.g. Schmalensee *et al.* 1998)*[56], and surveys of the use of the AEEI parameter in other climate policy models (Yates 1995)*[57]. The growth of energy efficiency slows overtime according to a logistic function, representing a process by which producers exhaust the technical potential for saving energy.

Technological versus structural change in MIT-EPPA

MIT-EPPA distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

Australian Bureau of Agriculture, Resource and the Environment (ABARE) Global Trade and Environment Model (GTEM)

General Structure of GTEM

For various reasons information was difficult to get for GTEM. The operators did not respond to emails and their documentation was incomplete. This was frustrating and unfortunate, as they seem to have an advanced understanding of the top-down bottom-up debate and included some advanced CGE techniques – Leontief functions to represent individual technologies in key sectors, Armington

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[55] Initial growth rates of energy efficiency: United States = 1.301%, Japan, the EC, other OECD = 1.210%, China = 1.980%, India = 1.430%, all former Soviet Bloc, Brazil, Rest of World, etc. = 1.100%.

[56] Schmalensee, R. T. Stoker and R. Judson. (1998). "World Carbon Dioxide Emissions: 1950-2050". *Review of Economics and Statistics,* 80, 15-27.

[57] Yates, A. (1995). "Autonomous Energy Efficiency Improvements: Relevance, Use and Empirical Basis for Global Warming Policy Analysis". Master's Thesis, Massachusetts Institute of Technology. Department of Electrical Engineering and Computer Science.

substitution to handle trade, etc. All the following information is derived from a semi-complete manual taken from their website.

GTEM is derived from MEGABARE.[58] Paraphrased from the anonymous author of the manual, an effort has been made in GTEM to move toward the realism of the 'bottom up' approach in modelling energy production technology while retaining the extensive interaction with other sectors of the economy obtained in 'top down' models.

Production in most sectors in GTEM is modelled using CES functions, intermixed with Leontief-like 'technical bundles' and CES functions using Armington substitution elasticities to replace foreign provision of intermediate inputs and final demand. All inputs of non-energy commodities and fuels can be domestic or foreign, following the Armington approach.

Technical bundles (equivalent to Leontiefs) are competed to get discrete stock values. Most sectors in GTEM use the standard nesting of CES and Leontief functions (Figure 17). The first Leontief split allocates between energy using inputs and non-energy commodity inputs. The next CES split allocates between the primary factors (capital, labour, land and resources) and energy, and then finally CES functions are used to break out the energy and primary factor inputs into their constituent components. Electricity and steel production instead use technical bundles, each equivalent to a Leontief production function, to represent

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[58] Cited as ABARE (1996), reference unavailable. All information downloaded from the Australian Bureau of Agriculture and Resources website for GTEM.
http://www.abare.gov.au/research/GTEM/GTEM.htm

the importance of individual technologies in these sectors. It was unclear how the technologies were competed, but given the given the similarity to SGM it may be surmised that they also compete their technologies using weighted life cycle costs.

Figure 17 Production function map for non-technology bundles industries in GTEM

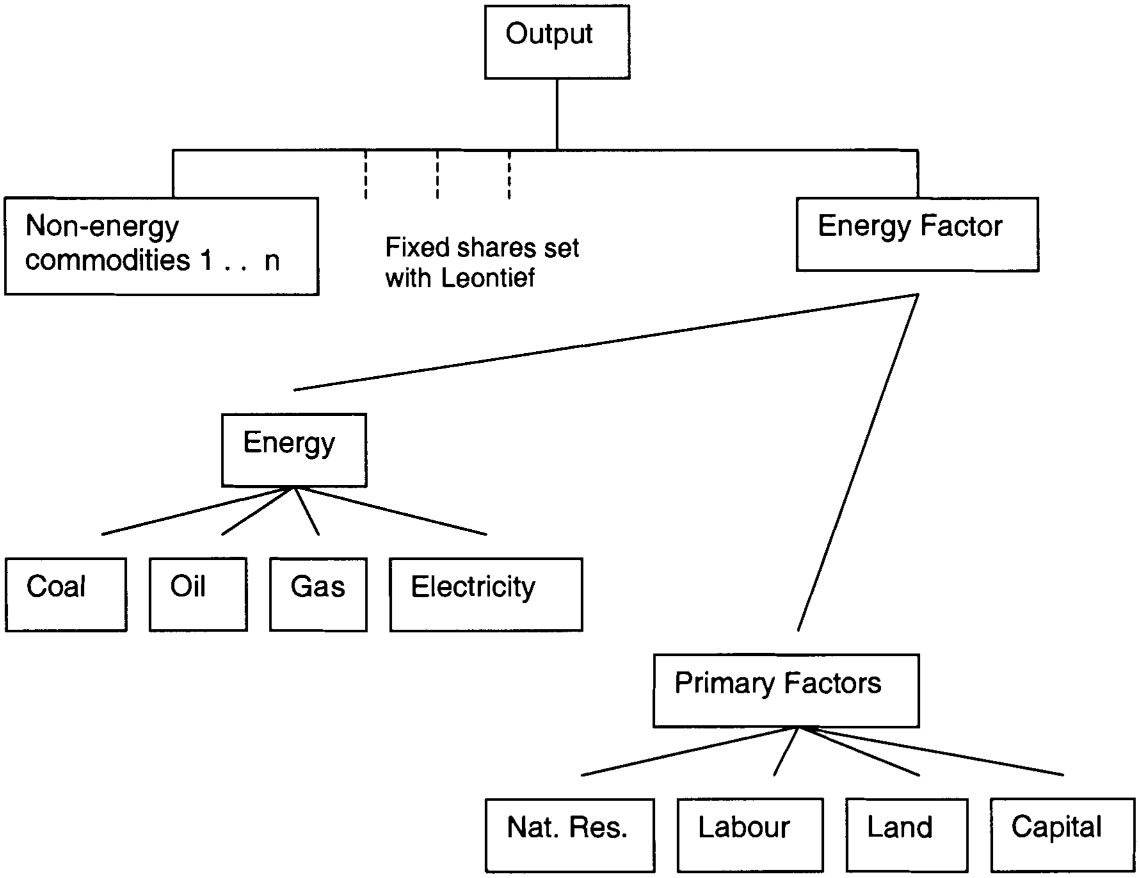
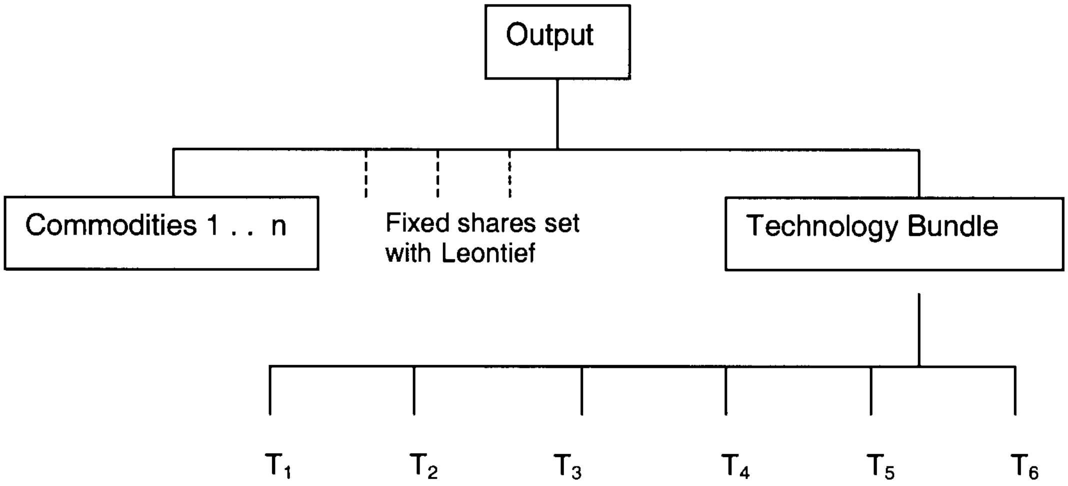


Figure 18 Production function map for technology bundle industries in GTEM



To avoid corner solutions GTEM's technology-bundle/Leontief approach is designed such that it is always possible for technologies to be smoothly substituted for one another in response to price changes, while the input structure of each technology remains unchanged. Thus, the approach does not capture possible lack of smoothness in substitution between technologies, which can be handled by 'bottom up' models. In other words, it does not capture the possibility that some discrete difference in the relative costs of using the alternative technologies may be required before substitution will occur. By modelling energy intensive industries in this way, GTEM restricts substitution to known technologies, thereby preventing technically infeasible combinations of inputs being chosen as model solutions, which is not necessarily the case with 'top down' models.

Using the 'technology bundle' approach electricity can be generated discretely from coal, petroleum, gas, nuclear, hydro or renewable based technologies, while iron and steel can be produced using blast furnace or electric arc technologies, all in response to changes in their relative costs.

Elasticity values in GTEM

I wrote away for these values, as they were not available in documentation. The authors did not respond.

AEEI in GTEM

GTEM's documentation indicates that they use some form of value to impose non-price induced technological change on their production functions. I wrote away for values but they did not respond. In quote from their website documentation;

> GTEM contains provision for simulating the impacts of various types of biased and neutral technical change. The standard definitions of the biases in technological change used in economics apply to a static situation where input prices are fixed. In general, equilibrium models, however, technological changes introduced in any form, inevitably, leads to changes in relative prices. Consequently, demand for various inputs may be affected accordingly. A technological change that may be unbiased at the industry level in a partial equilibrium setting may turn out to be 'biased' in terms of its impacts in a general equilibrium model. In this sense, it is very difficult to define a neutral technical progress that eventually ends being input-neutral in a general equilibrium model.
>
> It is nevertheless possible to focus on the impact of the technical change on input demand before the whole system is adjusted. It is this impact that has been taken to identify the nature of a technical change in GTEM, whether it is a neutral technical progress at regional or sectoral level or a technical progress that is biased towards saving some specific input in a specific industry.59

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[59] http://www.abare.gov.au/research/GTEM/GTEM.htm

Technological versus structural change in GTEM

GTEM distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

McKibben and Wilcoxen's G-Cubed

General Structure of G-Cubed

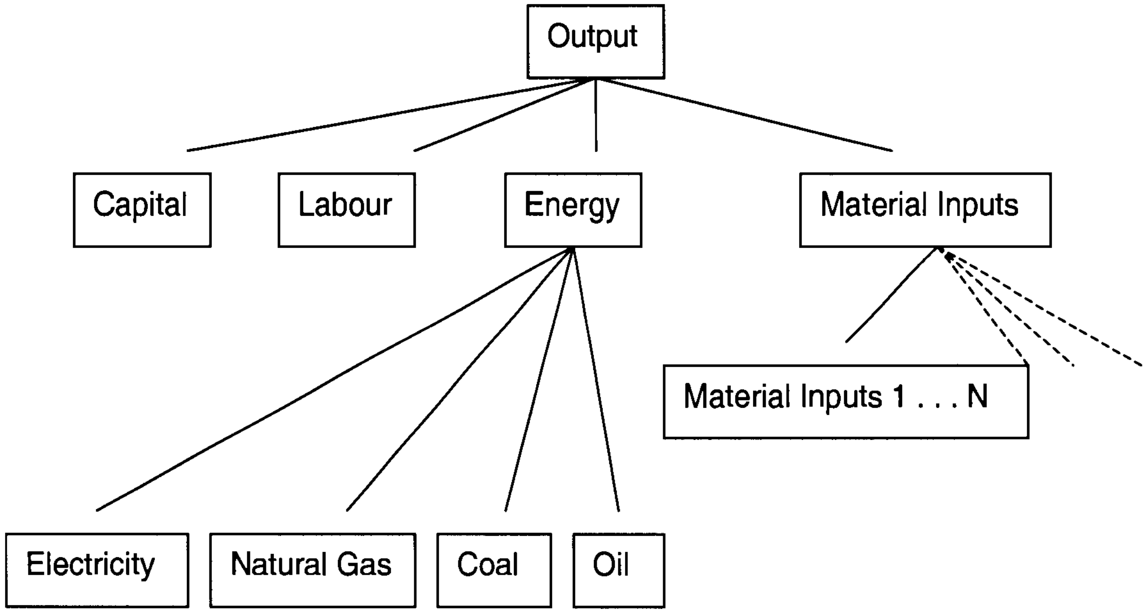
G-Cubed was built by W. McKibbin of the Australian National University and P. Wilcoxen of the University of Texas (McKibben and Wilcoxen 1999). It is also used by the US Environmental Protection Agency. G-Cubed‘s manual describes it as a detailed and broad scale model suitable for analyzing the effects of a wide range of policies on international trade and financial flows. According to their documentation it includes:

- Eight geographic regions
- 12 sectors in each region;
- International trade modelled at the bilateral level;
- Full endogenous international capital flows;
- Inter-temporal optimization used to model saving, investment, and international asset market arbitrage; where appropriate, the existence of liquidity constraint agents is taken into account;
- Behavioural parameters estimated from time series data whenever possible; and
- All budget constraints are satisfied at all times.

G-Cubed's key innovations, as seen by the authors, are inter-temporal optimization of savings and investment, combined with the econometric parameter estimates in full inter-temporal modelling of international trade and asset flows.

There are five energy sectors (electric utilities, natural gas utilities, petroleum processing, coal extraction, and crude oil and gas extraction) and seven non-energy sectors (mining, agriculture, forestry and wood products, durable manufacturing, non-durable manufacturing, transportation and services). Each firm's production technology is represented by a nested constant elasticity of substitution (CES) function. At the top tier, output is a function of capital, labour, energy, and materials. Below this level, there are energy and materials nests. Please see Figure 19 for the standard production function map.

Figure 19 CES production function map for a sector in G-Cubed



Elasticity values in G-Cubed

Table 38 Estimated parameter values in G-Cubed

Note: parameters with four decimal places are estimated.			
	Top-level Substitution Parameter	Energy Nest Substitution Parameter	Material Nest Substitution Parameter
Electric Utilities	0.7634	0.2	1
Gas Utilities	0.8096	0.9325	0.2
Oil Refining	0.5426	0.2	0.2
Coal Mining	1.703	0.1594	0.5294
Crude Oil and Gas Extraction	0.4934	0.1372	0.2
Other	1.0014	1.1474	2.7654
Agriculture	1.283	0.6277	1.7323
Forestry	0.9349	0.9385	0.1757
Durables	0.4104	0.8045	0.2
Non-durables	1.0044	1	0.0573
Transportation	0.5368	0.2	0.2
Services	0.2556	0.3211	3.0056

AEEI in G-Cubed

An autonomous efficiency component is included for each of the inputs to the top-level CES function. They use a 1% energy efficiency growth for all regions when generating the baseline.

Technological versus structural change in G-Cubed

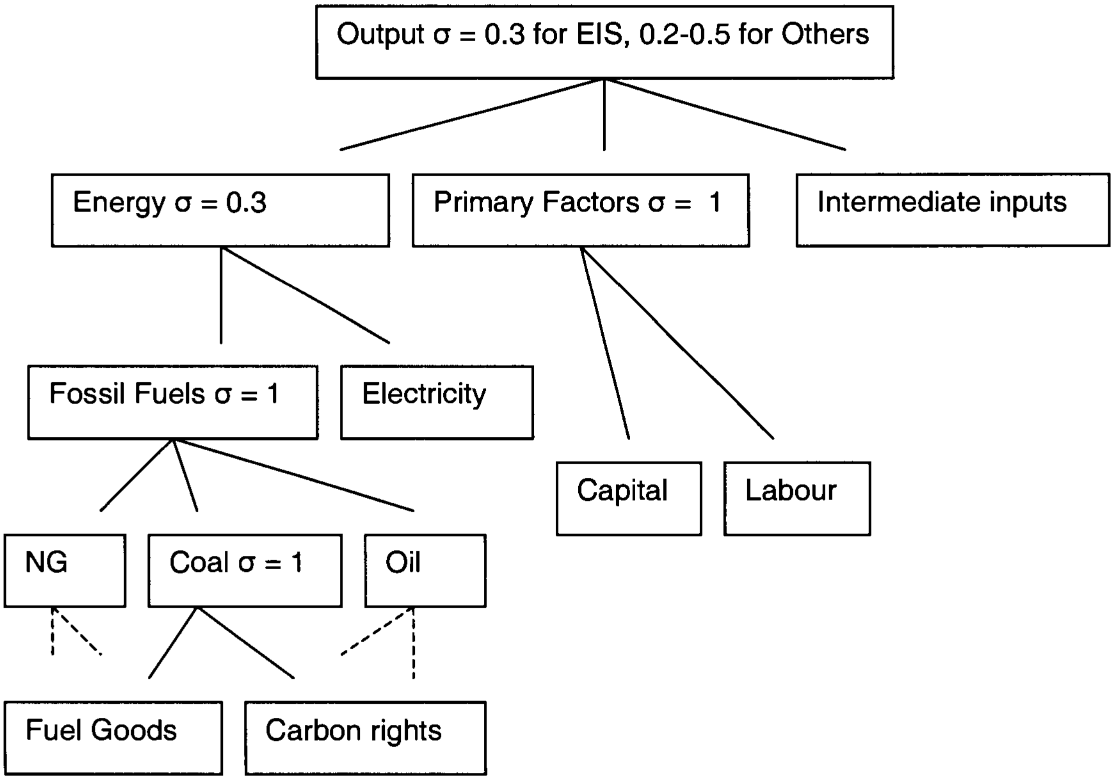
G-Cubed distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

Asia-Pacific Integrated Model (AIM)

General Structure of AIM

AIM is operated by the National Institute for Environmental Studies (NIES-Japan) and Kyoto University. It encompasses 21 geopolitical regions and handles seven energy goods (coal, crude oil, petroleum and coal products, natural gas, nuclear energy, renewable energy, electricity) and four non-energy goods: 1) energy intensive products, 2) agriculture, other manufactures and services, 3) transport and 4) savings. There are three sectors: firms, households, and government. All industries have an identical CES production structures (Figure 20).

Figure 20 AIM production function map



Elasticity values in AIM

See Figure 20 for values; they are guesstimates based on energy modelling norms.

AEEI in AIM

Not applicable

Technological versus structural change in AIM

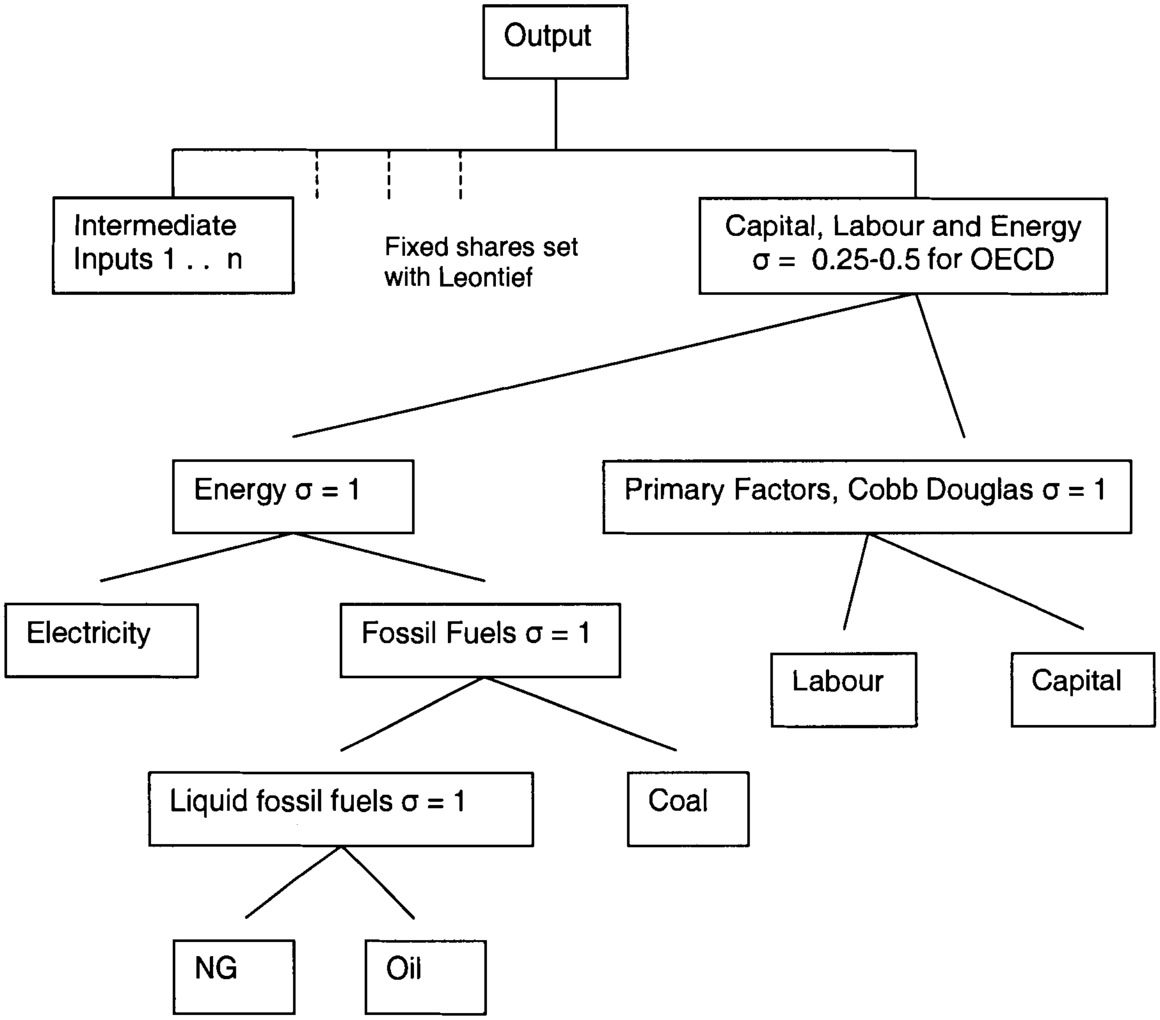
AIM distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

Multi-sector Multi-region Trade Model (MS-MRT)

General Structure of MS-MRT

Charles River Associates and the University of Colorado operate MS-MRT. It has nine industries: five energy production sectors (crude oil, RPP, coal, natural gas, electricity), agriculture, chemicals, other energy intensive sectors, and all other goods. All are structured according to the following general production function map (Figure 21).

Figure 21 General production function map for MS-MRT



Elasticity values in MS-MRT

To quote the operators, the elasticity between energy and value-added was based on the literature. Since energy is a small share of the total of value-added plus energy input, one can approximate this elasticity with the own-price elasticity for energy, which is in the range of 0.25 and 0.5. MS-MRT's inter-fuel elasticities are adjusted so that MS-MRT shows the same level of coal to gas switching as the NEMS model.

AEEI in MS-MRT

The AEEI in MS-MRT are adjusted in an iterative process so that they match the US DOE's Energy Information Administration's GDP and energy consumption forecasts. They start the recursive process with AEEI = 1%, then solve the model. If the energy consumption differs from the EIA forecast the AEEIs are adjusted up or down to match the forecast.

Technological versus structural change in MS-MRT

MS-MRT distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

The MACRO Family of Models: MERGE 3.0 (ETA-MACRO), MARKAL-MACRO, MACRO-MESSAGE, CETA

General Structure of the MACRO models

The MACRO top down model has been paired with several models with lesser and greater amounts of energy technology detail: ETA (later Global 2100, now MERGE 3.0), MARKAL and MESSAGE. MACRO is a simple long term optimal growth model with a single producer and consumer that lends itself to combination with technology models (Manne 1978). MACRO has gone through various permutations, but all have in common the same basic structure. A single consumer maximizes the discounted log of their consumption over time, calculated as income (production) minus capital investment and energy consumption. Income is generated through a simple nested CES structure for production; capital and labour are nested against an energy composite, which is usually the sum of energy demands, modified for efficiency, brought together with the capital and labour to produce output. Capital grows and depreciates linearly, while labour grows linearly. Equation 23 describes MACRO's CES production function.

$$Y = \left[\gamma K_t^{\rho\alpha} L_t^{\rho(1-\alpha)} + \sum b_{dm} (D_{dm,t})^{\rho} \right]^{1/\rho} \qquad (23)$$

α = share parameter for capital
ρ = substitution parameter, (K/L:E ESUB) = 1/1-ρ
γ & b = coefficients determined through the base year calibration
K = capital (grows and depreciates linearly with time)
L = labour (grows linearly with time)
Y = income or production
D = Energy demand from the energy model (ETA, MARKAL, MESSAGE)
b = Efficiency adjustment paramter for energy (AEEI, DDF, etc.)

$D_{dm,t}$ is a specific energy demand that comes from the detailed technology models. These demands are modified by the efficiency parameter b, a single AEEI in the case of ETA-MACRO and a sector specific demand-decoupling factor (DDF) in the case of MARKAL-MACRO. ESUB and AEEI must be exogenously specified prior to any runs, and all users have reported that results are critically influenced by these parameters. Of further note, because the entire economy in a given region has only one producer and consumer, no structural change at this level is possible, unless it occurs through the AEEI. A more detailed discussion of unique characteristics of the various models follows.

ETA-MACRO / Global 2100 / MERGE 3.0

ETA-MACRO, Global 2100 and MERGE 3.0 are successive versions of the same model by Manne and Richels. MERGE 3.0 is multi region version of the ETA-MACRO model, with each region having its own representative producer/consumer. ETA is a technologically detailed resource supply model. It describes the primary energy supply of fossil fuels, and secondary energy supply of electricity. The rest of the linkage between primary energy supply and final consumption by demand sectors is supplied by constant autonomous energy efficiency indices (Nyström 1995). Supply and demand are equilibrated within each individual time period, but there are "look ahead" features to allow for interactions between periods. It operates using a "putty-clay" system – older capital stocks are viewed as hard baked "clay", and subsequent investments are malleable "putty" which then become "clay" themselves in following periods. New vintages are chosen using a CES production function, while the mix of inputs for older vintages is fixed using Leontief style functions. This mix of fixed and flexible capital means price responsiveness is lower in the short-run than the long-run (Manne and Richels 1992).

Energy demands are divided into just two categories in ETA-MACRO: electric and non-electric. Energy for capital substitution is modelled through a single ESUB parameter. Paraphrased from Manne and Richels (1992), when energy costs are a small fraction of total output, the ESUB parameter is approximately equal to the absolute value of the price elasticity of demand. In ETA-MACRO / Global 2100 / MERGE, this parameter is measured at the point of secondary energy production: electricity at the bus bar, crude oil, and synthetic fuels at the refinery gate. For the OECD countries, the standard assumption is that ESUB is 0.4; that is, a 1% price increase will lead to a decline of 0.40% in the demand for energy. All non-priced induced energy efficiency changes are bundled into a single AEEI. For the OECD countries they use an AEEI of 0.5% annually throughout the 21st-century (Manne and Richels 1992).

CETA

CETA is based on ETA-MACRO/Global 2100, and is therefore its production function system is mostly identical, with a few key differences. The purpose of the model was to include warming and damage components; this added computational complexity to the system. To reduce this CETA takes a "putty/putty" approach; both old and new vintages of capital are malleable in input ratios. Since CETA has a putty-putty production function while Global 2100 has a putty-clay function, output in CETA responds without lags to changing prices and autonomous energy efficiency improvements. To compensate they use somewhat lower values for ESUB (0.3 instead of 0.3-0.4) and for AEEI (0.25% instead of 0.5%) so that their representation tracks the Global 2100 "putty / clay" representation for the same Stanford Energy Modelling Forum data.

MARKAL-MACRO

MARKAL-MACRO (Manne and Wene 1992) improves upon ETA-MACRO by explicitly including more of the energy transformation system. Besides primary supply, it also includes refining, heat production, distribution, end-use conversion, and energy conservation. The final step to the energy used by the production function is made via a demand-decoupling factor (DDF), which is analogous to the AEEI (Nyström and Wene 1999). Nyström provides an in-depth comparison of ETA-MACRO and MARKAL-MACRO. A key concept in MARKAL-MACRO is the demand decoupling factors or (DDF). These may be thought of as staged

AEEI that operate at different levels in the energy supply and demand system. The final values adopted are 0.75% per year for residential heat, 0.5% per year for commercial heat, and 0.25% per year for electrical appliances in both residences and commercial buildings. They were set by duplication of official demand forecasts and by deriving a relationship between historic economic growth and energy demand.

Nyström makes a key point about the elasticity of substitution parameter (ESUB). The further downstream towards primary energy supply one measures energy consumption, the lower the potential ESUB as one gradually eliminates substitution and efficiency improvements higher in the energy system. She used 0.4 for ESUB, with a value of 0.25 used for sensitivity analysis. She also reports that that other analysts, Schreper and Kram (1994) and Kypreos (1995), have used 0.2 and 0.3, respectively.

MACRO-MESSAGE

The key developments of MACRO-MESSAGE were a much more explicit depiction of technological development in the future. Specifically, this involved the use of technology curves to extrapolate increasing efficiency of technologies moving out in the future.

McKitrick's Estimated CGE Model for Canada

General Structure of McKitrick's Estimated CGE

McKitrick's CGE model is not operated by an institution like the other models in this study, but is important to this project for four reasons:

- It is built for Canada and is often mentioned by Canadian operators of economic models.
- It is mostly parameterized using estimated historical data instead of using guesstimates.
- McKitrick follows a unique approach to production function structure.
- McKitrick makes some key unique criticisms of the general CGE method.

In McKitrick's model, the Canadian economy is divided into four sectors: households, firms, the government, and the rest of the world. The productive side of the economy is broken into six sectors: agriculture, mining, refining, utilities, manufacturing, and services. The technology of each industry is represented by a short-run constant elasticity of substitution profit function with constant returns to scale. Ten domestic commodities plus two factors (labour and capital) are specified. Capital is fixed each period.

McKitrick uses an econometric approach for establishing the parameters for his CGE modelling, rather than the more common calibration approach. Following Jorgenson (1984), and in contrast to the standard calibration approach, as described in Shoven and Whalley (1992), each equation in this model is econometrically estimated on a single database specially constructed for the project. There are many arguments for this, one being that it permits the use of flexible functional forms. The model used for McKitrick (1998), while econometrically based, has nonflexible forms because it was part of an exercise in comparative CGE modelling, aimed at assessing the econometric approach against the calibration approach. He had planned to replace the CES and

Leontief equations with normalized quadratic functions, but the project was never completed. See McKitrick (1998) for details on the econometric critique of CGE modelling.

McKitrick foresees some of the parameter estimate issues raised in this thesis; in paraphrase, the simulations (he performed) involve price and quantity ranges well outside the span of historical data. Consequently, the validity of his projections depends on the ability of the CES functions that make up the model to accurately extrapolate out-of-sample behaviour. He argues more flexible functional forms might do a better job, although ensuring existence of equilibrium in response to a large policy might be a problem. Although McKitrick does not raise the issue of the validity of using historical data to simulate future behavior, he clearly articulates the criticism of using parameters derived from historical data that do not cover the relevant policies imposed on the model.

An interesting consequence of his approach is that instead of starting with a standard pattern for the production functions, he let the results of the econometric analysis determined the shape of production functions. This resulted in a different nesting pattern for almost every sector. The resulting structures and the estimated parameters are summarized in the following figures for manufacturing, services, mining, utilities, and petroleum refining.

Figure 22 Manufacturing production function map for McKitrick's CGE

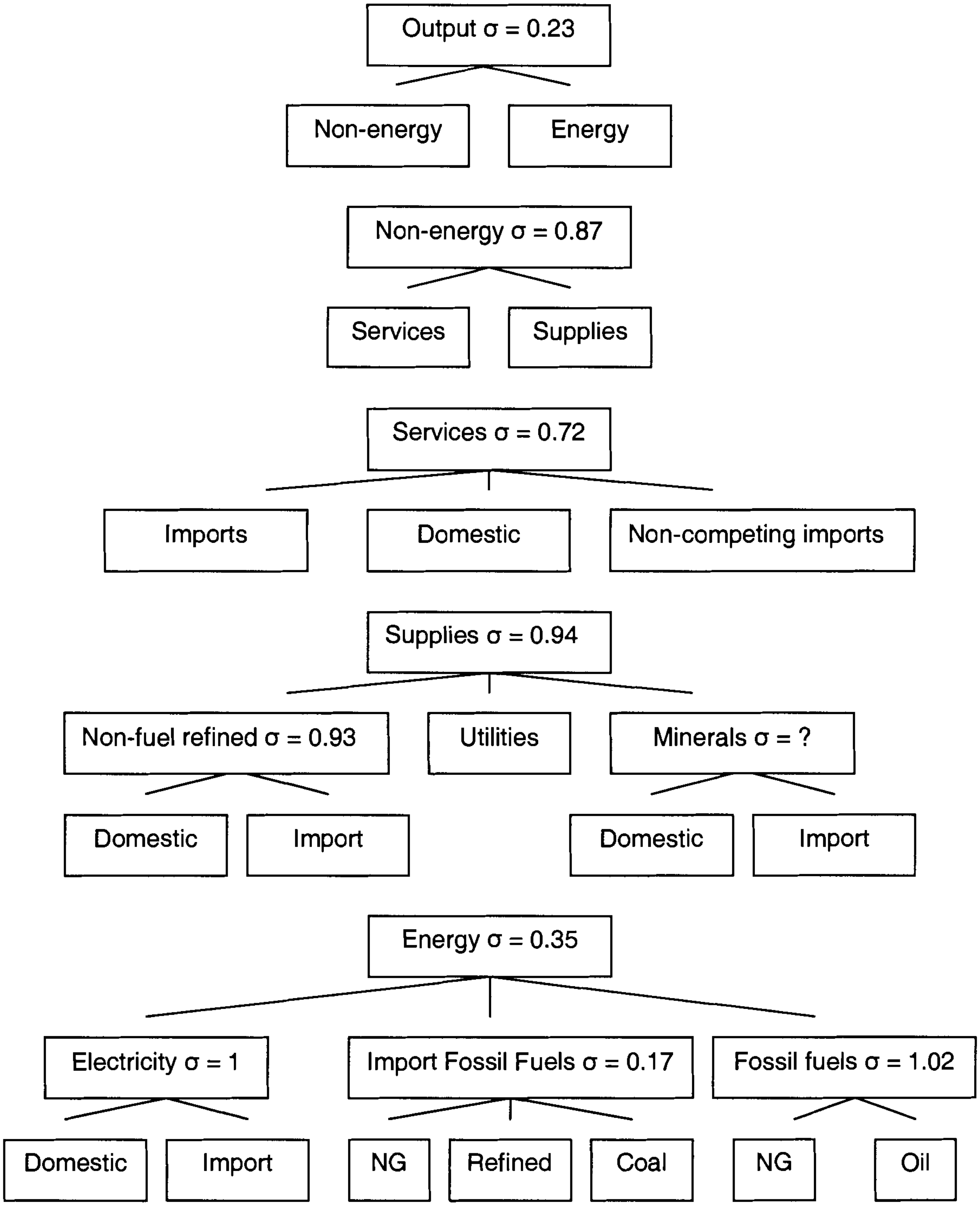


Figure 23 Services production function map for McKitrick's CGE

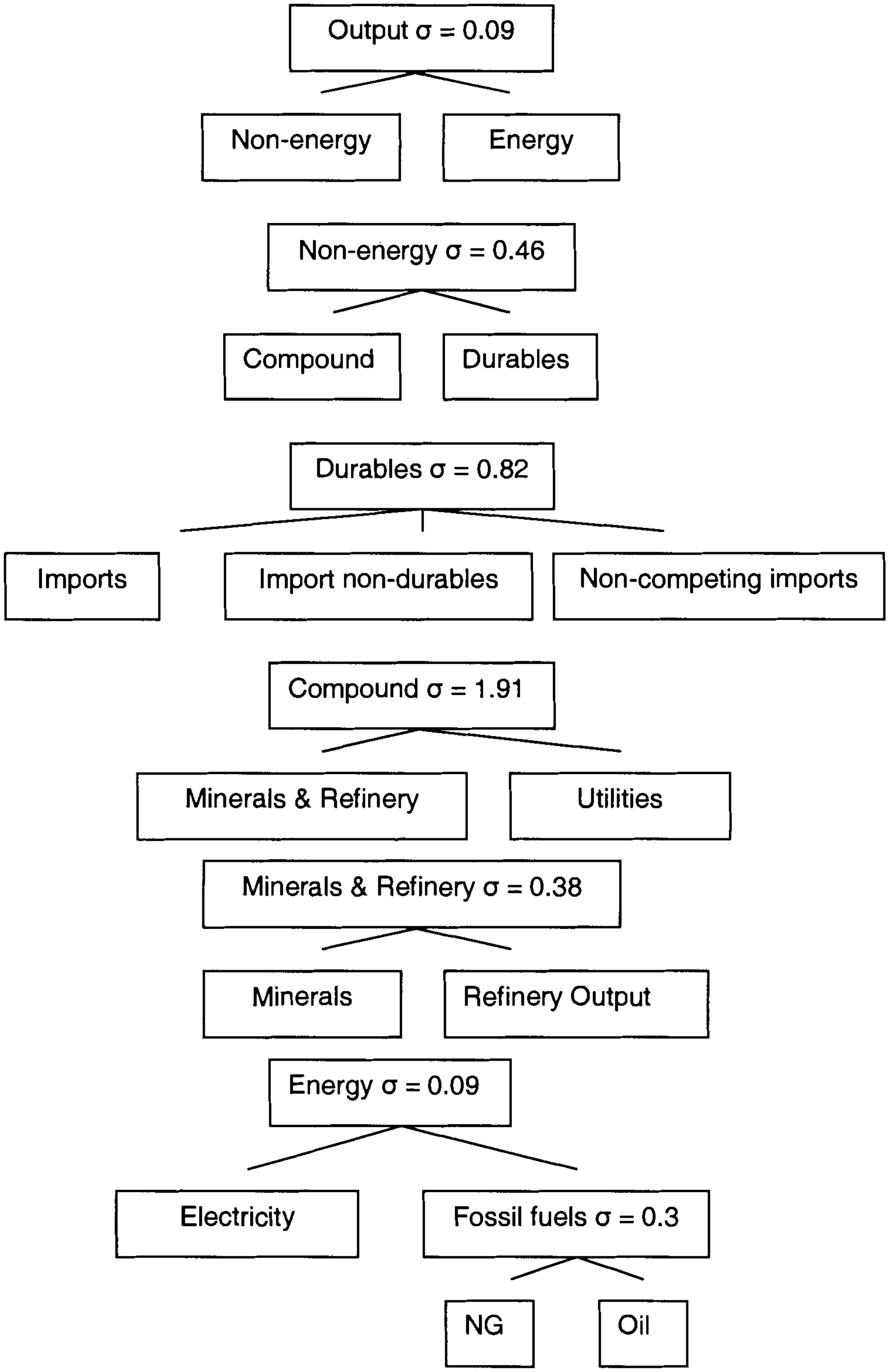


Figure 24 Mining production function map for McKitrick's CGE

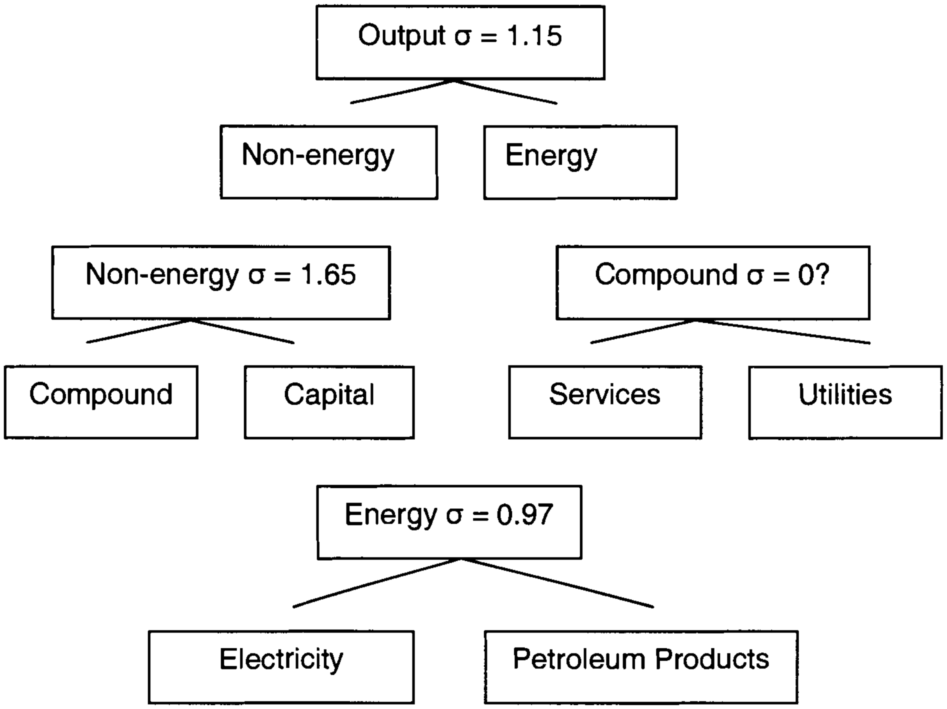


Figure 25 Utilities production function map for McKitrick's CGE

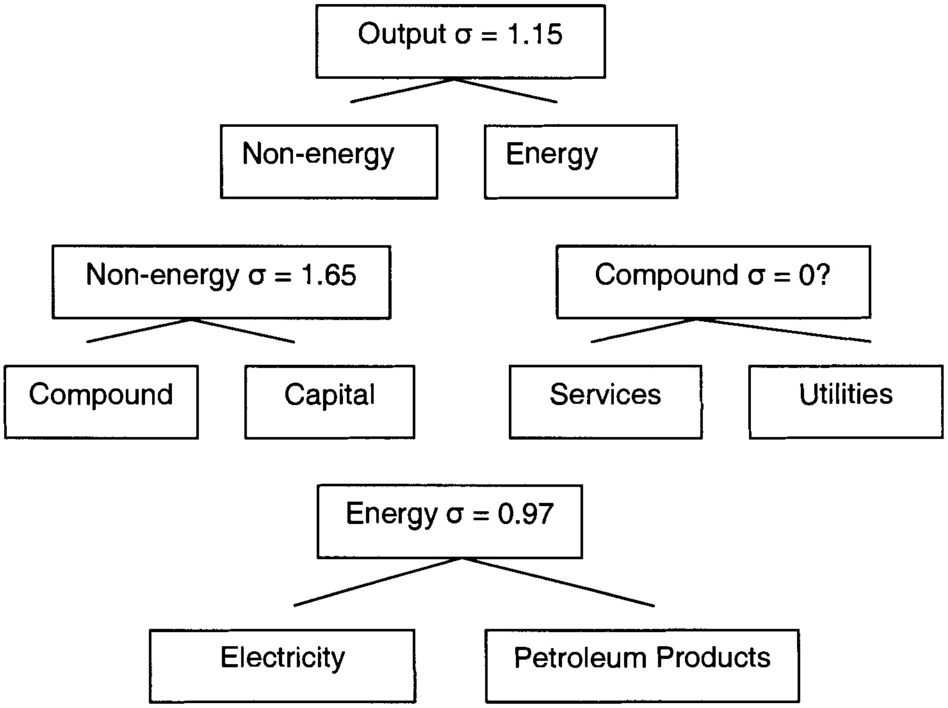
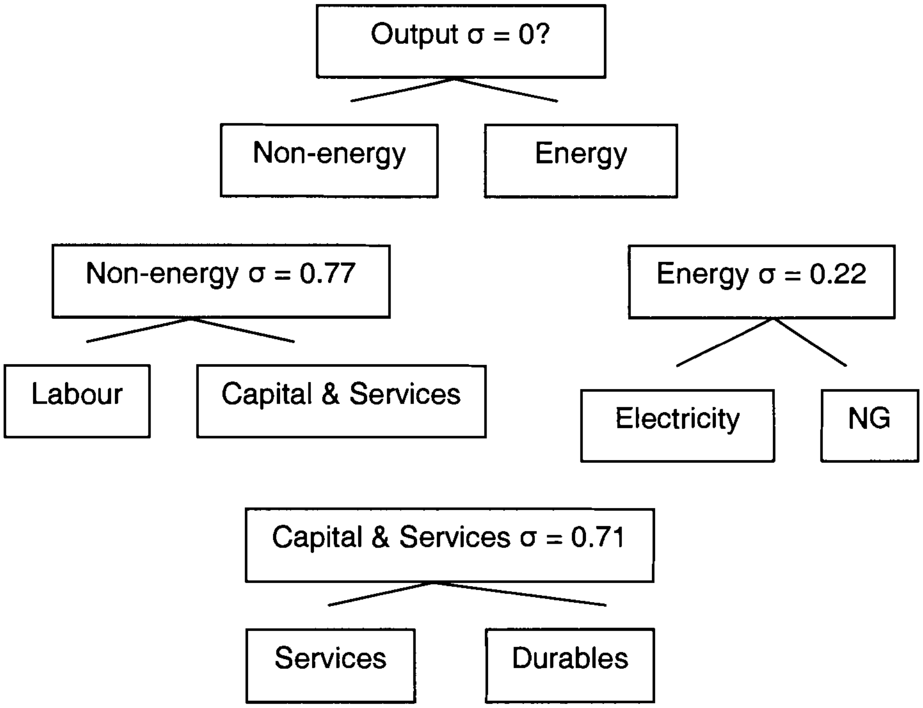


Figure 26 Refining production function map for McKitrick's CGE



Elasticity values for McKitrick's CGE

Included in Figures 22-26.

AEEI in McKitrick's CGE

The model uses a 0.5% annual efficiency improvement. McKitrick states the GHG emission levels are very sensitive to the chosen AEEI value, and consequently the results of all policy simulations will depend on this parameter. Some other models that allow for a lower value of AEEI also assume a non-polluting backstop energy source becomes available at a fixed world price, effectively adjusting the AEEI when the backstop is employed, but he did not employ this assumption.

Technological versus structural change in McKitrick's CGE

MS-MRT distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

Canadian Sectoral General Equilibrium Model (CASGEM)

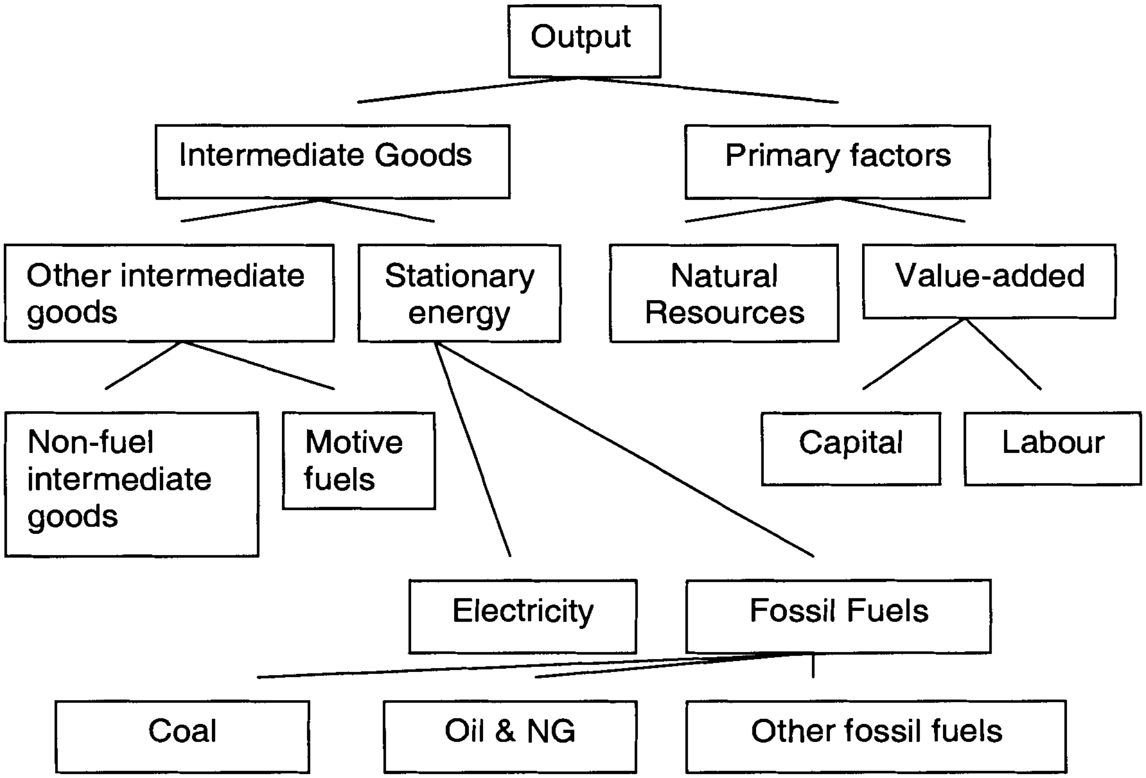
General Structure of CASGEM

CASGEM is operated by the Canadian Department of Finance. It is a large, single period (static) model of the Canadian economy with 51 sectors providing 59 goods and services based on the Canadian national accounting system. CASGEM simulations of an energy or GHG reduction policy may be interpreted as showing the long-run impact of a policy change after the economy has completed the possibly lengthy adjustment to the new policy. The long-run growth rate of the economy is assumed to be unchanged by the policy. CASGEM does not describe the transition of the economy from introduction of the policy to the time at which the economy has fully adjusted to the new policy.

The central driver in CASGEM, like most CGE models, is a representative consumer who maximizes their utility. Utility divides into current consumption and savings. Current consumption divides into leisure and goods. Goods divide between home energy and other goods. Other goods divide between other non-fuel goods and motive fuels. Home energy divides between electricity and fossil fuels. Fossil fuels divide between coal, natural gas, gas pipelines, and other are fossil fuels.

In most industries, production is characterized using CES functions exhibiting constant returns to scale; an X percent increase in all inputs leads to an X percent increase in output. This is consistent with the accompanying assumption of perfect competition in those industries, implying a horizontal supply curve and constant marginal cost. Exceptions are the seven industries with fixed factors; they have upward sloping supply curves. All inter-sector linkages are based on calibrated 1993 input-output tables. For those goods that do not have a single world price, the model incorporates an Armington specification for international trade. According to the Armington specification, the demand for an imported good rises as the price of the foreign good falls relative to the price of its domestically produced substitute. At all times, consumers buy at least some of the domestic good and some of the imported good, even when the price difference between the two is large. In other words, consumption never specializes completely in the foreign or domestically produced good. This helps to keep the model from making the unrealistic prediction that Canada entirely ceases production of some goods because of a small policy change. It also allows the model to be consistent with observed patterns of intra-industry trade; it allows the same commodity to be imported and exported at the same time, with the degree of substitution determined by the Armington elasticity. The price of capital is set on world capital markets; any additional capital desired by Canadians comes from world markets at the world price. All domestic production is modelled with the same generic CES production map (Figure 27). All elasticity values are in the Table 38.

Figure 27 CASGEM CES production function map



Elasticity values and sources: CASGEM

Table 39 Elasticities in CASGEM

Elasticity Type	Substitution between intermediate goods(including energy) and primary factors	Substitution between other intermediary goods and stationery energy	Substitution between Electricity and Fossil Fuels	Substitution between Fossil Fuels	Substitution between Non-fuel Goods and Motive Fuels	Substitution between fixed factors and value-added
Source of elasticities	McKitrick 1997, Wigle 1999, G-Cubed	Calibrated from own-price elasticities obtained from IFSD	Calibrated from own-price elasticities obtained from IFSD	Calibrated from own-price elasticities obtained from IFSD	Calibrated from own-price elasticities obtained from IFSD	Calibrated from own-price elasticities obtained from IFSD
Agriculture	0.7	0.35	1.08	1.17	0.34	0.09
Fishing, Trapping and Forestry	0.7	0.35	0.69	1.13	0.57	0.03
Mining	0.7	0.64	0.83	0.43	0.65	0.08
Iron Mining	0.7	0.67	0.74	0.38	0.76	0.03
Coal Mining	0.7	0.63	0.78	0.38	0.78	0.13
Oil and Gas Extraction	0.4	1.45	0.7	0.05	0.34	0.45
Food	0.4	0.6	0.91	2.01	0.56	0
Beverage Manufacturing	0.4	0.37	0.73	1.3	0.33	0
Tobacco	0.4	0.37	0.97	0.17	0.43	0
Rubber Products	0.4	0.37	1.01	0.56	0.43	0
Plastics	0.4	0.38	1.55	0.05	0.40	0
Textiles	0.4	0.37	0.85	1.13	0.41	0
Wood	0.4	0.37	1.15	0.61	0.66	0

Elasticity Type	Substitution between intermediate goods(including energy) and primary factors	Substitution between other intermediary goods and stationery energy	Substitution between Electricity and Fossil Fuels	Substitution between Fossil Fuels	Substitution between Non-fuel Goods and Motive Fuels	Substitution between fixed factors and value-added
Furniture and Fixtures	0.4	0.37	0.96	0.89	0.16	0
Pulp and Paper	0.4	0.23	0.78	1.07	0.64	0
Paper and Allied Industries	0.4	0.21	0.6	1.35	0.21	0
Printing and Publishing	0.4	0.6	1.22	1.79	0.43	0
Steel	0.4	0.38	0.55	1.13	0.70	0
Nonferrous Smelting	0.4	0.43	0.83	1.06	0.67	0
Secondary Metal	0.4	0.38	0.89	1	0.27	0
Metal Fabricating	0.4	0.37	0.86	1.2	0.36	0
Machinery	0.4	0.37	0.79	0.88	0.38	0
Transportation Equipment	0.4	0.37	0.88	0.91	0.38	0
Electrical Products	0.4	0.37	1.11	0.78	0.43	0
Cement	0.4	0.54	0.8	0.54	0.75	0
Nonmetallic Mineral Products	0.4	0.38	0.7	1.55	0.72	0
Petroleum and Coal Products	1	1.29	0.76	4	0.18	0
Chemical and Chemical Products	0.4	0.93	0.95	0.29	0.41	0
Agricultural & Other Chem. Prdcts.	0.4	0.99	0.93	0.09	0.16	0
Industrial Chemicals	0.4	1.26	0.93	0.73	0.37	0
Miscellaneous Manufacturing	0.4	0.37	1.05	0.88	0.42	0
Construction	0.2	0.22	0.83	4	0.12	0
Air Transport	0.2	0.5	0.49	4	0.29	0
Non-Air Transport	0.2	0.5	0.49	2.52	0.83	0

Elasticity Type	Substitution between intermediate goods(including energy) and primary factors	Substitution between other intermediary goods and stationery energy	Substitution between Electricity and Fossil Fuels	Substitution between Fossil Fuels	Substitution between Non-fuel Goods and Motive Fuels	Substitution between fixed factors and value-added
Storage	0.2	0.63	0.86	1.82	0.64	0
Gas Pipelines	0.5	0.65	0.94	2.46	0.76	0
Non-gas Pipelines	0.5	0.62	0.73	4	0.21	0
Communication	0.5	0.59	0.91	2.42	0.28	0
Electric Power	0.5	0.66	0.7	0.9	0.17	0.49
Wholesale Trade	0.2	0.61	0.95	2.96	0.36	0
Retail Trade	0.2	0.63	1.27	1.98	0.35	0
Finance, Insurance and Real Estate	0.2	0.62	0.91	1.69	0.31	0
Service to Business	0.2	0.6	1.03	1.93	0.41	0
Education	0.2	0.34	0.98	1.79	0.44	0
Health and Social Services	0.2	0.33	1.2	1.58	0.44	0
Accommodation and Food	0.2	0.61	1.08	1.69	0.1	0
Amusement and Recreation	0.2	0.61	1.02	1.46	0.41	0
Personal and miscellaneous services	0.2	0.62	0.99	2.19	0.42	0
Federal Government	0.2	0.33	0.98	2.03	0.05	0
Provincial and territorial governments	0.2	0.33	2.25	0.05	0.05	0
Consumers	NA	0.21	1.69	1.18	0.42	NA

AEEI in CASGEM

There is no apparent use of an AEEI in CASGEM, except perhaps for calibration. This may be because it is a single period model.

Technological versus structural change in CASGEM

CASGEM distinguishes structural from technology change like most CGE models; technology change occurs inside the production functions, while structural change occurs through allocation of demand via market clearing.

National Energy Modelling System (NEMS)

General structure of NEMS

The NEMS model of United States Department of Energy Information Administration is not strictly a top-down model like most of the others in this survey. It is one of the first genuine hybrid models in that it incorporates elements of both the top-down and bottom-up technology simulation approaches. What is interesting about it in this context, however, is the methodology used to incorporate macroeconomic effects, or the top-down portion of the model.

The MAM, or Macroeconomic Module, has gone through several methodological iterations in the recent past. Until 2001/2002 the MAM operated as a “response surface” model. The response surface, based on DRI’s macroeconomic model for the United States, can be thought of as a matrix of possible dynamics, based on elasticities, that feed back percentage changes in demand for given changes in prices and quantities in the NEMS transportation, residential, commercial, and industrial models. These responses were found to be too simplistic, however, in that there was no rebound in overall demand associated with structural readjustment to new prices. To improve the representation of the macroeconomy, in 1999 the NEMS research team installed kernel regressions in the place of single elasticity responses in the response surface. These kernel regressions incorporated the direct price responses that may be captured by single value elasticities, but also incorporated the structural changes that may occur afterwards, changes that would allow economic activity to rebound despite a permanent price increase in a given input. These kernel regressions based their coefficients on the DRI model.

In 2002, the response surface approach was traded for a simplified version of Global Insight's Model of the US economy. Their model is essentially a combination of a macro-econometric model and growth model that, while essentially Keynesian, includes various formulaic elements of the neoclassical/ monetary/supply side and rational expectations models that inform CGE practice. The model is complex, but from the perspective of this study the essential element is how it models production.

As a bottom-up/top-down hybrid, many of NEM's individual sectors are highly disaggregated and technologically explicit. This is true for its energy supply and conversion models, as well as the transportation model. The commercial and residential models are moderately disaggregated, while its industry model is quite simple, consisting mainly of efficiency curves. Because production is represented explicitly, the model does not require a production function for these sectors. However, these sub-models do not operate directly at the macro level, and for their effects to be felt at this level the macro model needs to represent them independently; how this is done is through a proxy production function.

Given the complexities of the financial side of the macroeconomic model, with its elaborate treatment of taxation, budgets, government revenue and labour income the production side of the macroeconomic model is surprisingly simple. They use a Cobb Douglas function with adjustments for factor input growth and improvements in total factor productivity. The Cobb Douglas assumes an elasticity of one (with constant returns to scale), and they include four inputs: labour with a cost share parameter of 64%, business capital at 26%, infrastructure (government capital) at 2% and energy at 7%. They do not include their values for improvements in total factor productivity in the documentation, but it can be surmised that these values are used to calibrate the model against past improvements in productivity.

AEEI in NEMS

As stated above, the productivity of the inputs to the Cobb Douglas production function are adjusted yearly. These values were not provided in the NEMS documentation; this is probably because the underlying DRI model is proprietary.

Technological versus structural change in NEMS

Because of the widely differing sector treatment in NEMS, how technological and structural change is handled varies widely. The more sophisticated the depiction of technology in a given model, the more technology change is handled here instead of by the input productivity adjustment parameters in the macroeconomic model. Transportation and electricity have the most detailed handling of technology, while industry had the least, with commercial and residential somewhere in between. Structural change is mostly managed by the macro model, but in transportation parts of it (specifically mode substitution) are managed at the sub-model level (as in CIMS).

Appendix C:
Production function types

Economic models of production generally require that production be depicted as a function that produces output from a combination of inputs. The following section outlines the main production function types, starting at the most simple and rigid and moving to the more complex and adaptable.

The most simple production function is a linear function where all inputs are perfectly substitutable for each other ($\sigma = \infty$), as described in Equation 24.

$$q(x_i \cdots_n) = (\alpha_1 X_1 + \alpha_2 X_2 + \ldots + \alpha_n X_n) \tag{24}$$

where q is output, $X_{i...n}$ are the various inputs, and $\alpha_{i...n}$ are fixed coefficients of $X_{i...n}$. The linear production function implies perfect substitutability between two or more inputs; if you have enough machines or labour, you can completely replace one with the other. This relationship is rarely found in the world; a mixture of inputs is usually required, or there is a preference for one input over another.

In contrast, fixed proportions relationships imply that one needs a fixed ratio of two or more inputs to create a given output; the elasticity of substitution is zero ($\sigma = 0$). This depiction of production is useful when one is trying to describe a given machine or process whose input mixture is fixed. The Leontief, or fixed-coefficient, production function is described in Equation 25.

$$q(x_i \cdots_n) = \alpha_0 \min(\alpha_1 x_1, \ldots, \alpha_n x_n) \tag{25}$$

All inputs $(x_{i \ldots n})$ are complements used in strict proportion (via coefficients $\alpha_{i \ldots n.})$ to produce output q. α_o is a technology parameter that allows output to rise with technical advances over time. This production function is simple and useful for short-term analysis and describing technology stock that is already in place, but not when there is any significant degree of substitutability between inputs. If one is trying to describe production in a sector in the future, or a production technology whose form may allow a large range of different input ratios, a production function is required that can accommodate different ratios of inputs. The simplest of these functions is the Cobb Douglas, described in Equation 26.

$$q(K, L) = AK^{\alpha_1} L^{\alpha_2} \tag{26}$$

where α_1 and α_2 are share coefficients, and sum to one when returns to scale are constant, the usually modelled case. In equation (26), A is a technology parameter that allows output to rise without increasing inputs. The Cobb Douglas production function has been used often in economic modelling because it provides a simple and clear depiction of the relationship between two inputs, capital and labour being the most common, for a given system of production. The multiple input Cobb Douglas is described in Equation 27.

$$q(x_i \cdots_n) = \prod_{i=1}^{n} x_i^{\beta_i} \text{ , where } \sum_{i=1}^{n} \beta_i = 1 \text{ for constant returns to scale.} \tag{27}$$

The Cobb-Douglas is restrictive when trying to approximate real systems. The constant returns to scale case assumes an elasticity of one, whereas the "real" substitution elasticity, guesstimated or estimated from historic data, may be some other value. The Constant Elasticity of Substitution function (CES) provides this (Arrow *et al.* 1961). The CES for the restricted case of capital and labour is described in Equation 28.

$$q(K,L) = \gamma\left[\partial K^{\rho} + (1-\partial)L^{\rho}\right]^{\varepsilon/\rho} \tag{28}$$

γ, which is more than zero, is an efficiency parameter that shifts the output of the whole production function. ∂, which is between zero and one, is a distribution parameter that permits the relative shares of K and L to vary in much the same way as the exponents in a Cobb-Douglas case. ρ, which is less than or equal to one, is the substitution parameter; the closer ρ is to one (its maximum value), the higher the elasticity of substitution. ε is a returns to scale parameter; the function exhibits increasing, constant or decreasing returns to scale depending on whether $\varepsilon > 1$, $\varepsilon = 1$, or $\varepsilon < 1$. The elasticity of substitution is $\sigma = 1/(1-\rho)$.

The CES function incorporates the linear, fixed proportions, and Cobb-Douglas functions as special cases (for $\rho = 1$, $-\infty$ and 0, respectively) (Nicholson 1992). The CES is by far the most commonly used production function in CGE models because it allows a large number of inputs while keeping the substitutability relationship simple and moderately flexible and seems to reflect the empirical capital for labour substitution relationship reasonably well (that is, with reasonable substitutability in the middle of the range, with increasing fixity towards using at least a bit of labour or capital towards the ends). The generalized multi input CES is described in Equation 29.

$$q(x_{i \ldots n}) = \alpha_0 \left[\sum_{i=1}^{N} (\alpha_i x_i)^\rho \right]^{\varepsilon / \rho} \qquad (29)$$

Output q is a function of inputs $x_{i \ldots n}$, efficiency coefficient α_0, share coefficients α_i, $i=1,\ldots,N$. N is the number of inputs to production.

A limitation of all versions of the CES production function is that it allows only one substitutability relationship between all the inputs. This may be applicable for two inputs but forces a common elasticity amongst three or more. Only by chance will the elasticity of substitution for any two inputs be the same as for any other two combinations of inputs. This blurs the substitutability relationship, which may sometimes be important, and sometimes not. If more than two inputs are required for a given output, modellers using the CES will often nest a sequence of two input relationships, each with its own substitutability relationship. These nesting systems can become quite elaborate, with between five and ten nesting levels in models, with many inputs and outputs. Nesting is accurate only if all the important relationships can be constructed as a hierarchy of input relationships, each with its own elasticity. If any of the important relationships require more than two inputs, this may indicate to the modeller that the CES should not be used, and a more generalized production function that does not require single elasticity relationships may be more appropriate.

Another characteristic of the CES that may be seen as either an advantage or limitation is that the elasticities do not change with input shares, hence the name "constant". Elasticities represent points on the curvature of a response surface drawn out by the production function; they can change as soon as a relative price change occurs. If the response surface is flat, all the elasticities for a given set of inputs are the same. In many cases, however, response surfaces tend to curve and eventually meet asymptotic "cut-offs" – cliffs and valleys in the response surface. Generalized production functions allow the elasticities to change under different input and price mixes.

There are two main types of generalized production function: the transcendental logarithmic frontier (translog) (Christensen *et al.* 1973) and the generalized Leontief (Diewart 1973). The key difference between these functions and the CES is the ability to accommodate elasticity relationships that change with input and price mixes. This capability is a mixed blessing for modellers. The translog function is described in Equation 30.

$$\ln q(x_{i \ldots n}) = \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln x_i + 0.5 \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \ln x_i \ln x_j \tag{30}$$

where q is output, the α's and β's are parameters to be estimated, $x_{i \ldots n}$ are the input quantities, and $\beta_{ij} = \beta_{ji}$ are imposed.

The $\beta_{ij} = \beta_{ji}$ condition states that the cross price substitutability relationships between inputs are symmetric (substitutability from capital to labour and from labour to capital is the same). This condition allows cost share equations, derived via Sheppard's Lemma, to be estimated as a system of equations. The Allen partial elasticities for the translog function are equal to:

Cross Input Elasticity of Substitution

$$\sigma_{ij} = \frac{\beta_{ij} + S_i S_j}{S_i S_j} \qquad \text{i,j =1...n but i} \neq \text{j} \tag{31}$$

Own-price Elasticity of Demand

$$\sigma_{ii} = \frac{\beta_{ii} + S_i^2 - S_i}{S_i^2} \qquad i = 1 \ldots n \tag{32}$$

where S_i and S_j represent the costs shares for the i^{th} and j^{th} inputs, and β_{ii} and β_{ij} are coefficients relating to the i^{th} and j^{th} inputs. The Allen partial elasticities represent the input elasticities of substitution adjusted for cost share, and as such allow comparison between inputs with different cost shares.

The generalized Leontief function is depicted in Equation 30 as follows, with similar variables and conditions to the translog;

$$q(x_{i \ldots n}) = \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \sqrt{x_i x_j} \tag{33}$$

Both these production functions share the advantage that they may replicate any production process with any number of inputs; elasticities in these forms may vary with input ratios and prices.

Appendix D:
Convergence routine for energy supply and demand in CIMS

BAU prices and quantities are taken as given from other sources, usually NRCan forecasts and Statistics Canada data. All policy prices are established as ratios of the BAU price in order to accommodate the diverging energy prices in each of industry, transportation, commercial and residential for the same energy commodity. The first policy run after the BAU has been run operates as follows.[60]

Necessary Variables and Data

$E_{P\,BAU}$ = BAU price of electricity, source NRCan

$R_{P\,BAU}$ = BAU price of a given RPP, source NRCan

$C_{P\,BAU}$ = BAU price of coal, source NRCan

$Cr_{P\,BAU}$ =BAU price of crude, source NRCan

$N_{P\,BAU}$ = BAU Price of NG, source NRCan

GHG_p = Policy price of greenhouse gases

$E_{P\,\text{Policy Run 1}\ldots\text{Policy Run N}}$ = Electricity price in each of the policy runs.

$R_{P\,\text{Policy Run 1}\ldots\text{Policy Run N}}$ = RPP price in each the policy runs.

$N_{P\,\text{Policy Run 1}\ldots\text{Policy Run N}}$ = NG price in each of the policy runs.

$Cr_{P\,\text{Policy Run 1}\ldots\text{Policy Run N}}$ = Crude price in each of the policy runs.

$C_{P\,\text{Policy Run 1}\ldots\text{Policy Run N}}$ = Coal price in each of the policy runs.

$R_{Q\,\text{BAU, Policy Run 1}\ldots\text{Policy Run N}}$ = Quantity of RPP demanded in each of the BAU and policy runs.

$N_{Q\,\text{BAU, Policy Run 1}\ldots\text{Policy Run N}}$ = Quantity of NG demanded in each of the BAU and policy runs.

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[60] I have used a different equation numbering system from the rest of the thesis as the following equations are to be treated as a sequential group.

$Cr_{Q\ \text{BAU, Policy Run 1}\ \ldots\ \text{Policy Run N}}$ = Quantity of Crude demanded in each of the BAU and policy runs.

$C_{Q\ \text{BAU, Policy Run 1}\ \ldots\ \text{Policy Run N}}$ = Quantity of Coal demanded in each of the BAU and policy runs.

$CLCC_{E,R,N,Cr,C}$ = Average unit cost of production for the current policy run for each of electricity, refining, natural gas extraction, crude extraction and coal mining.

$PLCC_{E,R,N,Cr,C}$ = Average unit cost of production for last policy run for each of electricity, refining, natural gas extraction, crude extraction and coal mining, which is the BAU in the first iteration

$X_{E,R,N,Cr,C}$ = % of the cost of production covered by ISTUM in each of electricity, refining, natural gas extraction, crude extraction and coal mining.

$Y_{E,R,N,Cr,C}$ = Convergence criterion. This is expressed as a maximum percentage difference in multiplier ratios between one run and the next. BAU is always the denominator value for the first iteration. 5% is the standard value, but it has been tested down to 3.5%. Below 3.5% stochastic variability in one of the ISTUM competition algorithms (TECH_COMPETE_SAMPLE) prevents convergence.

Equation 1: Finding the electricity demanded from the final demand models

$$E_{Q\ \text{Policy Run 1}}\ \text{Final demand sectors} = f(E_{P\ \text{BAU}}, R_{P\ \text{BAU}}, C_{P\ \text{BAU}}, Cr_{P\ \text{BAU}}, N_{P\ \text{BAU}}, GHG_p)$$

Equation 2: Finding the total electricity demanded in the first round

$$E_{Q\ \text{Policy Run 1}}\ \text{Total} = f(E_{Q\ \text{Policy Run 1}}\ \text{Final demand sectors}, E_{Q\ \text{BAU RPP}}, E_{Q\ \text{BAU NG}}\ E_{Q\ \text{BAU Crude}}, E_{Q\ \text{BAU Coal}}) = E_{Q\ \text{Policy Run 1}}\ \text{Final demand sectors} + E_{Q\ \text{BAU RPP}} + E_{Q\ \text{BAU NG}} + E_{Q\ \text{BAU Crude}} + E_{Q\ \text{BAU Coal}}$$

Equation 3: Finding the electricity price multiplier for the second round

$$E_{P\ \text{Policy Run 2}} = f(E_{P\ \text{BAU}}, CLCC_E, PLCC_E, X_E) = E_{P\ \text{BAU}} * (((CLCC/PLCC)*X_E)+(1-X_E))$$

Equation 4: Finding the RPP demand from the final demand sectors

$$R_{Q\ \text{Policy Run 1}}\ \text{Final demand sectors} = f(E_{P\ \text{BAU}}, R_{P\ \text{BAU}}, C_{P\ \text{BAU}}, Cr_{P\ \text{BAU}}, N_{P\ \text{BAU}}, GHG_p)$$

Equation 5: Finding the total RPP demand for the first round

$$R_{Q\ \text{Policy Run 1}}\ \text{Total} = f(R_{Q\ \text{Policy Run 1}}\ \text{Final demand sectors}, R_{Q\ \text{Policy Run 1 E}}, R_{Q\ \text{BAU NG}}\ R_{Q\ \text{BAU Crude}}, R_{Q\ \text{BAU Coal}})$$

Equation 6: Finding the RPP price multiplier for the second round

$$R_{P\ \text{Policy Run 2}} = f(R_{P\ \text{BAU}}, CLCC_R, PLCC_R, X_R) = R_{P\ \text{BAU}} * (((CLCC_R/PLCC_R)*X_R)+(1-X_R))$$

Equation 7: Finding the NG demanded from the final demand sectors in the first round

$$R_{Q\ \text{Policy Run 1}}\ \text{Final demand sectors} = f(E_{P\ \text{BAU}}, R_{P\ \text{BAU}}, C_{P\ \text{BAU}}, Cr_{P\ \text{BAU}}, N_{P\ \text{BAU}}, GHG_p)$$

Equation 8: Finding the total NG demanded in the first round

$$N_{Q\text{ Policy Run 1}}\text{ Total} = f(N_{Q\text{ Policy Run 1}}\text{ Final demand sectors}, N_{Q\text{ Policy Run 1 E}}, N_{Q\text{ Policy Run 1 R}}, N_{Q\text{ BAU Crude}}, N_{Q\text{ BAU Coal}})$$

Equation 9: Finding the NG price multiplier for the second round

$N_{P\text{ Policy Run 2}}$ = Fixed or set on North America supply curve.

Equation 10: Find the first round crude total demand and the second round price multiplier

$$Cr_{Q\text{ Policy Run 1}}\text{ Total} = f(R_{Q\text{ Policy Run 1 RPP}})$$

$Cr_{P\text{ BAU, Policy Run 1...N}}$ = Set exogenously to world price.

Equation 11: Finding the final demand sector demand for coal in round 1

$$C_{Q\text{ Policy Run 1}}\text{ Final demand sectors} = f(E_{P\text{ BAU}}, R_{P\text{ BAU}}, C_{P\text{ BAU}}, Cr_{P\text{ BAU}}, N_{P\text{ BAU}}, GHG_{p})$$

Equation 12: Finding the total demand for coal in round one

$$C_{Q\text{ Policy Run 1}}\text{ Total} = f(C_{Q\text{ Policy Run 1}}\text{ Final demand sectors}, C_{Q\text{ Policy Run 1 E}}, C_{Q\text{ Policy Run 1 R}}, C_{Q\text{ BAU Crude}})$$

Equation 13: Finding the coal price multiplier for round 2

$C_{P\text{ Policy Run 2}}$ = Fixed or set on supply curve.

Equation 14: The decision rules for convergence of the interior, energy supply/demand loop

IF any of : $(E_{P\text{ Policy Run 2}}, R_{P\text{ Policy Run 2}}, N_{P\text{ Policy Run 2}}, Cr_{P\text{ Policy Run 2}}, C_{P\text{ Policy Run 2}} > Y_{E,R,N,Cr,C})$ THEN start Policy Run 2 using:

$$(E_{P\text{ Policy Run 2}}, R_{P\text{ Policy Run 2}}, N_{P\text{ Policy Run 2}}, Cr_{P\text{ Policy Run 2}}, C_{P\text{ Policy Run 2}}) * (E_{P\text{ BAU}}, R_{P\text{ BAU}}, N_{P\text{ BAU}}, Cr_{P\text{ BAU}}, C_{P\text{ BAU}})$$

Repeat equations 1 through 14 until 14 has determined convergence.

Appendix E:
Detailed sources and mapping of CIMS' demand substitution elasticities

CIMS Sector Subdivisions	Divisions in Source Data, if Applicable	Source Value from Wirjanto (1999)	Initial Value	Value used
Commercial				
	Financial, insurance, real estate services	-1.11	-1.10	-0.55
	Business and computer services	-1.15		
	Private education services	-1.11		
	Health and social services	-1.19		
	Amusement and recreation services	-1.15		
	Accommodation services and meals	-1.24		
Transportation				
Personal transport	Source: Michaelis and Davidson (1996)	-0.05 (pkt) or -0.2 (fuel)	-0.10	-0.05
Chemical products				
Chlor- alkali	Industrial Chemicals	-0.88	"	-0.44
Sodium Chlorate	Industrial Chemicals	-0.88	"	-0.44
Hydrogen Peroxide	Industrial Chemicals	-0.88	"	-0.44
Ammonia Methanol	Industrial Chemicals	-0.88	"	-0.44
Polymers	Plastics Products	-1.66	"	-0.83
Industrial Minerals				
Cement	Concrete and concrete products	-3.51	"	-1.75
Lime	Other non-metallic mineral products	-1.05	"	-0.53
Glass	Other non-metallic mineral products	-1.05	"	-0.53
Bricks	Other non-metallic mineral products	-1.05	"	-0.53
Mining				
Open-pit	Iron ores and concentrates	-2.23	-2.75	-1.38
Underground	Other metal ores and concentrates	-3.79	-2.75	-1.38
Potash	Fertilizers	-1.15	-1.15	-0.58

CIMS Sector Subdivisions	Divisions in Source Data, if Applicable	Source Value from Wirjanto (1999)	Initial Value	Value used
Metal Smelting				
Lead	Other non-ferrous metal products	-1.18	"	-0.59
Zinc	Other non-ferrous metal products	-1.18	"	-0.59
Copper	Copper and copper alloy products	-1.14	"	-0.57
Aluminium	Raw aluminium and alloy products	-1.17	"	-0.59
Nickel	Nickel and nickel alloy products	-1.17	"	-0.59
Other Manufacturing				
Food, tobacco & beverages	Unmanufactured tobacco	-0.22	-0.75	-0.38
	Tobacco products	-0.54		
	Misc. food products	-1.18		
Rubber and plastics	Tires and tubes	-3.31	-2.00	-1.00
	Other rubber products	-1.86		
Leather, textile & clothing	Leather and leather products	-2.47	-1.50	-0.75
	Yarns and fibres	-1.40		
	Fabrics	-1.47		
	Other textiles products	-1.67		
	Hosiery and knitted products	-1.84		
	Other clothing and accessories	-1.41		
Wood products	Plywood and veneer	-1.64	-1.70	-0.85
	Other wood products	-1.78		
	Lumber and wood products	-1.72		
Furniture, printing & machinery	Furniture and fixture	-2.57	-1.50	-0.75
	Boilers, tanks and plates	-1.42		
	Metal building products	-1.23		
	Other metal fabricated product	n/a		
	Agricultural machinery	n/a		
	Other industrial machinery	-0.65		
Transportation equipment	Motor vehicles	-1.66	-2.00	-1.00
	Motor vehicle parts	-2.52		
	Transport equipment and repairs	-2.17		
Electrical & Electronic Equipment & Others	Electrical and electronic products	-2.01	-1.22	-0.61
	Appliances and household equipment	-1.64		
	Other manufactured products	-1.22		

CIMS Sector Subdivisions	Divisions in Source Data, if Applicable	Source Value from Wirjanto (1999)	Initial Value	Value used
Iron and Steel				
Slabs	Primary iron and steel products	-1.20	"	-0.60
Blooms	"	-1.20	"	
Billets	"	-1.20	"	
Molten Steel	"	-1.20	"	
Pulp and Paper				
Pulp export	Wood pulp	-3.44	"	-1.72
Newsprint	Newsprint, paper and building boards	-3.08	"	-1.54
Coated	Coated paper and paper products	-1.58	"	-0.79
Linerboard	Newsprint, paper and building boards	-3.08	"	-1.54
Uncoated	Newsprint, paper and building boards	-3.08	"	-1.54
Tissue	Newsprint, paper and building boards	-3.08	"	-1.54

Appendix F: The transcendental logarithmic production function

The transcendental logarithmic production function, or "translog", was chosen to regress the pseudo data because it is a highly general functional form, one that places no *a priori* restrictions of the Allen elasticities of substitution. The translog was originally developed by L.R. Christensen, D.W. Jorgensen, and L.J. Lau (Christensen *et al.* 1973), and is here derived from Berndt (1991), Nicholson (1992) and Griffin (1977).

$$\ln q(x_{i...n}) = \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln x_i + 0.5 \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \ln x_i \ln x_j \qquad (34)$$

where q is output, the α's and β's are parameters to be estimated, $x_{i...n}$ are the inputs, and $\beta_{ij} = \beta_{ji}$ are imposed.

The production function must be homogenous of degree 1 in prices.[61] This implies the following homogeneity restrictions:

$$\sum_{i=1}^{n} \alpha_i = 1, \ \sum_{i=1}^{n} \beta_{ij} = \sum_{i=1}^{n} \beta_{ji} = 0 \qquad (35)$$

These conditions also enforce constant returns to scale.

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[61] In a function that is homogenous of degree 1 the proportional input mix remains the same if all input prices are changed by the same proportion.

One could estimate the translog production function directly, but it is more efficient to estimate the optimal, cost minimizing input demand equations, transformed here into cost share equations. If one logarithmically differentiates the translog with respect to input prices and then employs Sheppard's Lemma, one obtains cost share (not input-output) equations of the following form.

$$\frac{\partial \ln q}{\partial \ln p} = \frac{p_i}{q} \bullet \frac{\partial q}{\partial p_i} = \frac{P_i X_i}{q} = \alpha + \sum_{i=1}^{n} \beta_{ij} \ln P_j \tag{36}$$

where

$$\sum\nolimits_{i=1}^{n} P_i X_i = C \tag{37}$$

Defining the cost shares $S_i \equiv P_i X_i / C$, it follows that

$$\sum_{i=1}^{n} Si = 1 \tag{38}$$

In my five input (Capital, Electricity, Natural Gas, Oil (Refined Petroleum Products) and Coal) system the translog cost function becomes the following cost share equations.

$$\begin{aligned}
S_{(K)} &= \alpha_K + \beta_{KK} \ln(P_K) + \beta_{KE} \ln(P_E) + \beta_{KN} \ln(P_{NG}) + \beta_{KO} \ln(P_C) + \beta_{KC} \ln(P_O) \\
S_{(E)lec} &= \alpha_E + \beta_{KE} \ln(P_K) + \beta_{EE} \ln(P_E) + \beta_{EN} \ln(P_{NG}) + \beta_{EO} \ln(P_C) + \beta_{EC} \ln(P_O) \\
S_{(N)G} &= \alpha_N + \beta_{KN} \ln(P_K) + \beta_{EN} \ln(P_E) + \beta_{NN} \ln(P_{NG}) + \beta_{NO} \ln(P_C) + \beta_{NC} \ln(P_O) \\
S_{(O)il} &= \alpha_O + \beta_{KO} \ln(P_K) + \beta_{EO} \ln(P_E) + \beta_{NO} \ln(P_{NG}) + \beta_{OO} \ln(P_C) + \beta_{OC} \ln(P_O) \\
S_{(C)oal} &= \alpha_C + \beta_{KC} \ln(P_K) + \beta_{EC} \ln(P_E) + \beta_{NC} \ln(P_{NG}) + \beta_{OC} \ln(P_C) + \beta_{CC} \ln(P_O)
\end{aligned} \tag{39}$$

where each of $S_{(K,E,N,O,C)}$ are the input cost shares of each input, each of $P_{(K,E,NO,OC)}$ are the input prices, $\alpha_{(K,E,N,O,C)}$ are base estimated cost shares, and the β's are estimated coefficients that relate the log of the price of capital and each energy type to the cost share of the relevant input. In the absence of symmetry conditions there are 30 parameters to estimate, seven in each of the five share equations. When the eleven cross equation symmetry conditions are imposed ($\beta_{KE}=\beta_{EK}$, $\beta_{KN}=\beta_{NK}$, $\beta_{KO}=\beta_{OK}$, $\beta_{KC}=\beta_{CK}$, $\beta_{EN}=\beta_{NE}$, $\beta_{EO}=\beta_{OE}$, $\beta_{EC}=\beta_{CE}$, $\beta_{NC}=\beta_{CN}$, $\beta_{NO}=\beta_{ON}$, $\beta_{NC}=\beta_{CN}$, $\beta_{OC}=\beta_{CO}$), the number of parameters drops to 19.

The homogeneity restriction requires that the translog function be homogenous of degree 1 in input prices. Equation 40 describes the homogeneity restrictions in the above (K, E, N, O, C) framework.

Homogeneity restrictions

$$\begin{aligned}
&\alpha_K + \alpha_E + \alpha_N + \alpha_O + \alpha_C = 1 \\
&\beta_{KK} + \beta_{KE} + \beta_{KN} + \beta_{KO} + \beta_{KC} = 0 \\
&\beta_{KE} + \beta_{EE} + \beta_{EN} + \beta_{EO} + \beta_{EC} = 0 \\
&\beta_{KN} + \beta_{EN} + \beta_{NN} + \beta_{NO} + \beta_{NC} = 0 \\
&\beta_{KO} + \beta_{EO} + \beta_{NO} + \beta_{OO} + \beta_{OC} = 0 \\
&\beta_{KC} + \beta_{EC} + \beta_{NC} + \beta_{OC} + \beta_{CC} = 0 \\
&\beta_{KY} + \beta_{EY} + \beta_{NY} + \beta_{OY} + \beta_{CY} = 0
\end{aligned} \tag{40}$$

These seven restrictions reduce the number of free parameters to be estimated from 19 to 12.

To implement this share equation system empirically, it is necessary to specify a stochastic framework. Researchers have typically added a random disturbance term e_i to each share equation, i = K, E, N, O, C and have then assumed that the resulting disturbance vector $e \equiv \{e_K, e_E, e_N, e_O, e_C\}$ is multivariate normally distributed with mean vector zero and constant covariance matrix Ω^* (Berndt 1991). This work proceeds likewise.

The share equation system possesses a special property, in that for each observation the sum of the dependent variables (the cost shares) over all equations always equals 1. Hence, if there are N factor share equations, N-1 of them are linearly independent. This adding up feature of the share equation system has several important econometric implications.

First, since the shares always sum to unity and only N-1 of the share equations are linearly independent, for each observation the sum of the disturbances across equations must always equal zero. This implies that the disturbance covariance matrix Ω is singular and non-diagonal.

Second, because the cost shares sum to unity at each observation, when the six symmetry restrictions are not imposed, the simple arithmetic of equation by equation ordinary least squares yields parameter estimates that always obey the following column sum adding-up conditions:

$$a_{KOM} + a_{Elec} + a_{NG} + a_{Oil} + a_{Coal} = 1 \tag{41}$$
$$g_{KK} + g_{KE} + g_{KN} + g_{KO} + g_{KC} = g_{KE} + g_{EE} + g_{EN} + g_{EO} + g_{EC} = 0$$
$$g_{KN} + g_{EN} + g_{NN} + g_{NO} + g_{NC} = g_{KO} + g_{EO} + g_{NO} + g_{OO} + g_{OC} = 0$$
$$g_{KC} + g_{EC} + g_{NC} + g_{OC} + g_{CC} = g_{KY} + g_{EY} + g_{NY} + g_{OY} + g_{CY} = 0$$

where the a_i and g_{ij} are estimates of the α_i and β_{ij} parameters. These relationships also imply that the OLS residuals e_i across equations will sum to zero at each observation, that is,

$$e_K + e_{Elec} + e_{NG} + e_{Oil} + e_{Coal} = 0 \tag{42}$$

Thus the residual cross products matrix resulting from OLS equation-by-equation estimation will be non-diagonal and singular.

Third, because the disturbance covariance and residual cross products matrices will both be singular, ML estimation, which minimizes the determinants of E'E, will not be feasible, since this determinant will be zero for any set of parameters satisfying the adding up conditions. The most common procedure for handling this singularity problem is to drop an arbitrary equation and then estimate the remaining N-1 share equations by (M)aximum (L)iklihood. Use of the ML estimation process makes the parameter estimates independent of which equation is deleted.

In this work the least cost share equations for each sub-sector were deleted. If coal had the least cost share, the 16 free parameters in the K, E, N, and O equations were directly estimated as the following system of equations:

$$\begin{aligned}
S_{(K)} &= \alpha_K + \beta_{KK} \ln(P_K/P_C) + \beta_{KE} \ln(P_E/P_C) + \beta_{KN} \ln(P_{NG}/P_C) + \beta_{KO} \ln(P_O/P_C) \qquad (43) \\
S_{(E)} &= \alpha_E + \beta_{KE} \ln(P_K/P_C) + \beta_{EE} \ln(P_E/P_C) + \beta_{EN} \ln(P_{NG}/P_C) + \beta_{EO} \ln(P_O/P_C) \\
S_{(N)} &= \alpha_N + \beta_{KN} \ln(P_K/P_C) + \beta_{EN} \ln(P_E/P_C) + \beta_{NN} \ln(P_{NG}/P_C) + \beta_{NO} \ln(P_O/P_C) \\
S_{(O)} &= \alpha_O + \beta_{KO} \ln(P_K/P_C) + \beta_{EO} \ln(P_E/P_C) + \beta_{NO} \ln(P_{NG}/P_C) + \beta_{OO} \ln(P_O/P_C)
\end{aligned}$$

Indirect estimates of the five other parameters in the omitted coal / oil share equation may then be estimated by rearranging the homogeneity restrictions in terms of the directly estimated parameters as follows:

$$\begin{aligned}
\alpha_C &= 1 - (\alpha_E+\alpha_N+\alpha_O+\alpha_K) \qquad (44) \\
-\beta_{KC} &= (\beta_{KK}+\beta_{KE}+\beta_{KN}+\beta_{KO}) \\
-\beta_{EC} &= (\beta_{KE}+\beta_{EE}+\beta_{EN}+\beta_{EO}) \\
-\beta_{NC} &= (\beta_{KN}+\beta_{EN}+\beta_{NN}+\beta_{NO}) \\
-\beta_{CC} &= (\beta_{KC}+\beta_{EC}+\beta_{NC}+\beta_{OC})
\end{aligned}$$

Since these indirectly estimated parameters are linear combinations of the directly estimated coefficients, variances of the indirectly estimated parameters can be calculated as a linear combination of the directly estimated variances and covariances.

The parameter estimates of the coal equation may also be estimated by eliminating any other factor. In testing the translog estimation system I considered it prudent to estimate, one by one, all the possible share equation combinations, and thereby ascertain that the system is invariant to the equation omitted. The parameter estimates were found to be the same across all equations.

The n-1 share equations were estimated as system of equations with bilateral symmetry imposed. Statistical testing for a diagonal covariance matrix was carried out with both the Breusch Pagan LM test and the likelihood ratio test. Both test statistics were compared against a Chi Square distribution with a preset level of significance.

The Allen partial elasticities of substitution for the translog function are described in Equations 45 and 46.

Cross Price Elasticity Of Demand

$$\sigma_{ij} = \frac{\beta_{ij} + S_i S_j}{S_i S_j} \qquad \text{i,,j = 1, . . ., n but i} \neq \text{j} \qquad (45)$$

Own-price Elasticity Of Demand

$$\sigma_{ii} = \frac{\beta_{ii} + S_i^2 - S_i}{S_i^2} \qquad \text{i = 1, . . . , n} \qquad (46)$$

Several further comments should be made concerning the substitution elasticity estimates. First, parameter estimates and fitted shares should replace the β's and S's when computing estimates of the σ's. This implies that in general the estimated elasticities will vary across observations. Second, since the parameter estimates and fitted shares have variances and covariances, the estimated substitution elasticities also have stochastic distributions. The fact that these elasticities are highly non-linear functions of the estimated β 's and S's has made it difficult to obtain estimates of the variances of the estimated elasticities. Progress on this is an ongoing problem in the econometrics literature, but in practice the mean of the estimates is taken (Nicholson 1992, p.205).

As already noted, this work, following the example of others in the field, proceeds on the assumption of bilateral symmetry; i.e. K for E = E for K. This assumption is necessary for the translog formulation to apply. In basic terms, this assumption requires that in the long-run, one can exchange the relevant inputs with equal ease. While interesting as an abstract concept, long-run historical consumption behaviour is normally characterized by one way transference between inputs because consumers, within their production frontier, will gradually reduce their use of less marginally productive inputs, and increase their use of more marginally productive inputs. It can be expected that even if the long-run substitutability between two inputs is theoretically equal, measurement of real data, or a pseudo data approximation of real data, will more often than not demonstrate more ease of transference from one input to the other. If, however, one assumes equal marginal productivity between the inputs at a single point in time, in this case a future point 20 years in the future when all capital and fuel use has rebalanced to reflect the changed relative cost of energy, one may assume bilateral symmetry. It is on this basis that I allowed myself this assumption. Nonetheless I conducted the normal Breusch Pagan covariance test (Chi square distribution) for bilateral symmetry. These results are in the CD appendix. As expected, most of the models did not pass this test at the 95% confidence level, although most were not far off.

The estimated translog cost function was checked to ensure that it was monotonically increasing[62] and strictly quasi-concave in input prices, as is required by theory. For monotonocity it is also required that the fitted shares all be positive, and for strict quasi concavity, the n x n matrix of substitution elasticities must be negative, semi-definite at each observation. Finally, a useful check on the validity of the elasticity calculations is to ensure that at each observation the additive relationship holds, i.e. that the sum of all price elasticity relationships adds to one.

The SHAZAM (V.9) econometrics computer program (Whistler *et al.* 2002) was used to do the econometrics.

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[62] Monotonocity requires that demand for a good decreases as the price of the good increases.

Appendix G:
Detailed results of the ESUB experiments

Table 40 National capital for energy elasticities of substitution by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	0.02	0.18	0.32	0.11	0.02	0.31
Energy feedbacks	0.00	0.14	0.33	0.02	0.04	0.10
No feedbacks	0.01	0.15	0.36	0.02	0.05	0.10
Share of energy ($)	1.60%	1.43%	0.27%	0.95%	1.43%	2.88%
"	1.59%	1.42%	0.27%	0.96%	1.42%	2.95%
"	1.59%	1.41%	0.27%	0.95%	1.41%	2.94%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	0.01	0.24	0.33	0.08
Energy feedbacks	0.01	0.19	0.30	0.08
No feedbacks	0.03	0.21	0.32	0.08
Share of energy ($)	3.34%	10.72%	17.15%	49.55%
"	3.32%	10.80%	17.23%	49.25%
"	3.31%	10.76%	17.19%	49.37%

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	0.39	0.20	-0.26	-0.07	-0.10
Energy feedbacks	0.38	0.19	-0.29	-0.09	-0.07
No feedbacks	0.39	0.18	-0.28	-0.07	-0.10
Share of energy ($)	0.13%	5.40%	3.23%	2.05%	0.45%
"	0.13%	5.43%	3.24%	2.12%	0.45%
"	0.13%	5.37%	3.28%	2.14%	0.44%

All Canada	Total All	Total w/o Trans	Energy $(000's)
All feedbacks	0.13	0.27	108,463,115
Energy feedbacks	0.12	0.23	109,147,410
No feedbacks	0.12	0.25	109,109,009

Table 41 National capital for electricity elasticities of substitution by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Metal Smelting	Pulp & Paper
All feedbacks	0.05	0.14	-0.18	0.16	0.01	0.59
Energy feedbacks	0.04	0.10	-0.13	-0.05	0.04	0.25
No feedbacks	0.04	0.11	-0.12	-0.05	0.04	0.27
Share of energy ($)	3.39%	3.88%	0.37%	1.12%	3.88%	6.88%
"	3.35%	3.83%	0.36%	1.12%	3.83%	7.07%
"	3.33%	3.82%	0.36%	1.11%	3.82%	7.04%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	0.01	0.21	0.61	0.16
Energy feedbacks	0.02	0.16	0.58	-0.56
No feedbacks	0.02	0.17	0.58	-0.69
Share of energy ($)	6.36%	27.41%	40.75%	0.24%
"	6.29%	27.49%	40.57%	0.24%
"	6.27%	27.37%	40.76%	0.24%

Supply Models	Coal	Elec	NG	Crude	Refining
All feedbacks	0.17	NA	-0.27	-0.20	0.46
Energy feedbacks	0.17	NA	-0.31	-0.19	0.42
No feedbacks	0.16	NA	-0.32	-0.19	0.44
Share of energy ($)	0.13%	NA	5.15%	2.19%	0.25%
"	0.13%	NA	5.14%	2.28%	0.25%
"	0.13%	NA	5.17%	2.28%	0.25%

All Canada	Total All	Total w/o Trans	Energy $(000's)
All feedbacks	0.33	0.33	32,637,591
Energy feedbacks	0.28	0.28	32,997,916
No feedbacks	0.28	0.29	32,999,907

Table 42 National capital for natural gas elasticities of substitution by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	-0.09	0.14	0.59	0.21	0.20	-0.34
Energy feedbacks	-0.11	-0.03	0.52	0.17	0.14	-0.30
No feedbacks	-0.08	-0.01	0.61	0.18	0.25	-0.29
Share of energy ($)	3.22%	1.21%	0.38%	1.82%	1.21%	3.12%
"	3.19%	1.21%	0.39%	1.80%	1.21%	3.22%
"	3.20%	1.20%	0.38%	1.81%	1.20%	3.11%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	-0.09	0.15	-0.35	0.07
Energy feedbacks	-0.08	0.07	-0.38	-0.48
No feedbacks	-0.04	0.14	-0.33	-0.46
Share of energy ($)	7.43%	10.82%	25.81%	0.53%
"	7.36%	10.83%	25.96%	0.53%
"	7.35%	10.83%	25.57%	0.53%

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	-0.05	0.26	-0.25	-0.07	-0.15
Energy feedbacks	-0.04	0.16	-0.27	-0.12	-0.07
No feedbacks	-0.04	0.23	-0.25	-0.07	-0.15
Share of energy ($)	0.11%	25.42%	10.53%	7.67%	1.45%
"	0.11%	25.27%	10.40%	7.78%	1.48%
"	0.11%	25.24%	10.70%	8.02%	1.47%

All Canada	Total all	Energy $(000's)
All feedbacks	-0.05	17,361,352
Energy feedbacks	-0.10	17,723,501
No feedbacks	-0.05	17,496,867

Table 43 National capital for RPP substitution elasticities by sector

Demand Models

Industry	**Chemicals**	**Mining**	**Cement/Lime**	**Iron & Steel**	**Smelting**	**Pulp & Paper**
All feedbacks	0.39	0.30	0.72	0.01	-0.54	-0.50
Energy feedbacks	0.43	0.32	0.76	0.00	-0.35	-0.31
No feedbacks	0.39	0.33	0.75	0.01	-0.50	-0.40
Share of energy ($)	0.12%	0.07%	0.11%	0.05%	0.07%	0.60%
"	0.11%	0.06%	0.10%	0.05%	0.06%	0.56%
"	0.12%	0.07%	0.11%	0.05%	0.07%	0.60%

Other	**Manufacturing**	**Commerce**	**Residential**	**Transportation**
All feedbacks	0.49	0.79	-0.37	0.08
Energy feedbacks	0.47	0.81	-0.45	0.08
No feedbacks	0.44	0.86	-0.31	0.08
Share of energy ($)	0.45%	1.42%	1.45%	94.07%
"	0.43%	1.41%	1.45%	94.16%
"	0.45%	1.43%	1.46%	94.04%

Supply Models	**Coal Mining**	**Electricity**	**Natural Gas**	**Crude Ext.**	**Pet. Refining**
All feedbacks	0.64	0.35	NA	0.45	-0.32
Energy feedbacks	0.63	0.28	NA	0.62	-0.34
No feedbacks	0.64	0.33	NA	0.47	-0.32
Share of energy ($)	0.13%	0.61%	NA	0.30%	0.27%
"	0.13%	0.62%	NA	0.31%	0.25%
"	0.13%	0.62%	NA	0.32%	0.26%

All Canada	**Total all**	**Total w/o Trans**	**Energy $(000's)**
All feedbacks	0.08	0.04	56,947,076
Energy feedbacks	0.08	0.03	56,903,029
No feedbacks	0.09	0.09	57,100,454

Table 44 National capital for coal elasticities of substitution by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	0.16	0.99	0.68	-0.03	-0.28	-1.00
Energy feedbacks	0.93	0.99	0.68	-0.04	-0.12	-1.00
No feedbacks	0.68	0.99	0.69	-0.05	-0.21	1.00
Share of energy ($)	0.03%	2.24%	3.24%	21.41%	2.24%	0.00%
"	0.03%	2.22%	3.24%	21.48%	2.22%	0.00%
"	0.03%	2.25%	3.25%	21.64%	2.25%	0.00%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	-1.00	0.00	0.00	0.00
Energy feedbacks	-0.99	0.00	0.00	0.00
No feedbacks	-0.88	0.00	0.00	0.00
Share of energy ($)	0.05%	0.00%	0.00%	0.00%
"	0.05%	0.00%	0.00%	0.00%
"	0.05%	0.00%	0.00%	0.00%

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	0.32	-0.07	NA	0.00	0.00
Energy feedbacks	0.32	0.27	NA	0.00	0.00
No feedbacks	0.34	-0.07	NA	0.00	0.00
Share of energy ($)	0.78%	72.18%	NA	0.00%	0.00%
"	0.78%	72.12%	NA	0.00%	0.00%
"	0.79%	71.92%	NA	0.00%	0.00%

All Canada	Total all	Energy $(000's)
All feedbacks	-0.04	1,517,096
Energy feedbacks	0.21	1,522,964
No feedbacks	-0.04	1,511,781

Table 45 National electricity for natural gas elasticities of substitution by sector

Demand Models

Industry	**Chemicals**	**Mining**	**Cement/Lime**	**Iron & Steel**	**Smelting**	**Pulp & Paper**
All feedbacks	0.05	0.43	0.62	0.06	0.25	0.41
Energy feedbacks	0.01	0.37	0.48	0.55	0.17	-0.24
No feedbacks	0.01	0.40	0.49	0.59	0.23	-0.30
Share of energy ($)	3.62%	3.21%	0.40%	1.48%	3.21%	6.07%
"	3.59%	3.17%	0.40%	1.47%	3.17%	6.23%
"	3.57%	3.16%	0.39%	1.47%	3.16%	6.18%

Other	**Manufacturing**	**Commerce**	**Residential**	**Transportation**
All feedbacks	0.30	2.66	2.98	-3.00
Energy feedbacks	0.26	2.84	2.96	-1.10
No feedbacks	0.28	2.85	2.98	-3.00
Share of energy ($)	7.33%	23.56%	38.70%	0.37%
"	7.25%	23.58%	38.59%	0.37%
"	7.22%	23.52%	38.59%	0.37%

Supply Models	**Coal Mining**	**Electricity**	**Natural Gas**	**Crude Ext.**	**Pet. Refining**
All feedbacks	1.34	NA	0.91	0.02	-0.57
Energy feedbacks	1.36	NA	0.91	0.04	-0.74
No feedbacks	1.21	NA	0.91	0.03	-0.63
Share of energy ($)	0.13%	NA	8.43%	4.45%	0.73%
"	0.13%	NA	8.39%	4.58%	0.74%
"	0.13%	NA	8.51%	4.64%	0.73%

All Canada	**Total all**	**Total w/o Trans**	**Energy $(000's)**
All feedbacks	1.91	1.85	45,948,217
Energy feedbacks	1.91	1.92	46,608,963
No feedbacks	1.91	1.93	46,451,319

Table 46 National electricity for RPP elasticities of substitution by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	0.77	1.63	1.23	-0.67	-0.02	0.81
Energy feedbacks	0.76	1.72	1.65	-0.38	0.01	0.61
No feedbacks	0.54	1.54	1.06	-0.60	-0.07	0.11
Share of energy ($)	1.34%	1.49%	0.21%	0.45%	1.49%	2.95%
"	1.33%	1.48%	0.20%	0.45%	1.48%	3.02%
"	1.33%	1.47%	0.20%	0.45%	1.47%	3.03%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	1.34	2.11	2.99	1.51
Energy feedbacks	1.41	2.61	2.99	1.52
No feedbacks	1.32	1.85	2.99	1.54
Share of energy ($)	2.66%	11.14%	16.13%	61.27%
"	2.64%	11.24%	16.17%	61.07%
"	2.64%	11.19%	16.22%	61.08%

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	1.44	NA	NA	0.30	-0.10
Energy feedbacks	1.52	NA	NA	0.20	1.30
No feedbacks	1.44	NA	NA	0.23	-0.12
Share of energy ($)	0.13%	NA	NA	1.01%	0.27%
"	0.13%	NA	NA	1.06%	0.26%
"	0.13%	NA	NA	1.06%	0.26%

All Canada	Total all	Total w/o Trans	Energy $(000's)
All feedbacks	1.73	1.96	87,554,990
Energy feedbacks	1.79	2.23	87,853,908
No feedbacks	1.70	1.94	88,039,309

Table 47 National electricity for coal loss to cities of substitution by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	-0.36	2.95	2.69	3.00	3.00	-3.00
Energy feedbacks	-0.01	2.95	2.41	3.00	3.00	0.60
No feedbacks	-1.12	2.93	2.51	3.00	3.00	-1.80
Share of energy ($)	14.01%	21.79%	2.74%	11.59%	21.79%	6.94%
"	13.97%	21.70%	2.74%	11.65%	21.70%	7.15%
"	13.92%	21.73%	2.73%	11.66%	21.73%	7.13%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	-3.00	NA	NA	NA
Energy feedbacks	-2.67	NA	NA	NA
No feedbacks	-3.00	NA	NA	NA
Share of energy ($)	34.84%	NA	NA	NA
"	34.73%	NA	NA	NA
"	34.77%	NA	NA	NA

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	3.00	NA	NA	NA	NA
Energy feedbacks	3.00	NA	NA	NA	NA
No feedbacks	3.00	NA	NA	NA	NA
Share of energy ($)	0.86%	NA	NA	NA	NA
"	0.86%	NA	NA	NA	NA
"	0.86%	NA	NA	NA	NA

All Canada	Total all	Energy $(000's)
All feedbacks	0.01	5,963,721
Energy feedbacks	0.42	5,975,981
No feedbacks	-0.02	5,952,728

Table 48 National natural gas for RPP elasticities of substitution by sector

Demand Models

Industry	**Chemicals**	**Mining**	**Cement/Lime**	**Iron & Steel**	**Smelting**	**Pulp & Paper**
All feedbacks	3.00	0.65	2.25	1.69	2.76	2.95
Energy feedbacks	2.89	1.17	2.18	1.65	2.41	2.95
No feedbacks	2.49	0.85	2.26	1.67	2.60	2.95
Share of energy ($)	0.93%	0.37%	0.18%	0.51%	0.37%	1.30%
"	0.93%	0.37%	0.18%	0.51%	0.37%	1.31%
"	0.93%	0.36%	0.18%	0.51%	0.36%	1.31%

Other	**Manufacturing**	**Commerce**	**Residential**	**Transportation**
All feedbacks	2.99	1.60	2.76	1.00
Energy feedbacks	2.99	1.54	2.73	1.00
No feedbacks	2.99	1.55	2.74	1.00
Share of energy ($)	2.28%	3.96%	7.84%	79.25%
"	2.28%	4.00%	7.98%	78.99%
"	2.27%	3.99%	7.81%	79.16%

Supply Models	**Coal Mining**	**Electricity**	**Natural Gas**	**Crude Ext.**	**Pet. Refining**
All feedbacks	0.99	NA	NA	1.01	2.76
Energy feedbacks	0.98	NA	NA	0.81	2.74
No feedbacks	0.99	NA	NA	1.01	2.75
Share of energy ($)	0.13%	NA	NA	2.22%	0.60%
"	0.13%	NA	NA	2.29%	0.60%
"	0.13%	NA	NA	2.33%	0.59%

All Canada	**Total all**	**Total w/o Trans**	**Energy $(000's)**
All feedbacks	1.27	2.25	67,715,205
Energy feedbacks	1.27	2.27	67,951,501
No feedbacks	1.26	2.27	67,953,218

Table 49 National natural gas for coal elasticities of substitution by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	-2.82	2.81	2.62	0.08	1.96	3.00
Energy feedbacks	-2.82	2.81	2.58	0.02	1.93	3.00
No feedbacks	-2.82	2.81	2.70	0.03	1.54	-3.00
Share of energy ($)	6.68%	3.35%	1.55%	8.77%	3.35%	2.25%
"	6.69%	3.36%	1.57%	8.75%	3.36%	2.34%
"	6.74%	3.37%	1.56%	8.88%	3.37%	2.27%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	-1.82	NA	NA	NA
Energy feedbacks	-2.13	NA	NA	NA
No feedbacks	-2.90	NA	NA	NA
Share of energy ($)	17.67%	NA	NA	NA
"	17.68%	NA	NA	NA
"	17.74%	NA	NA	NA

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	3.00	2.13	NA	NA	NA
Energy feedbacks	3.00	2.12	NA	NA	NA
No feedbacks	3.00	2.17	NA	NA	NA
Share of energy ($)	0.39%	59.15%	NA	NA	NA
"	0.39%	59.03%	NA	NA	NA
"	0.40%	58.86%	NA	NA	NA

All Canada	Total all	Energy $(000's)
All feedbacks	0.95	7,300,006
Energy feedbacks	0.88	7,378,235
No feedbacks	0.62	7,256,076

Table 50 National RPP for coal elasticities of substitution by sector

Demand Models

Industry	**Chemicals**	**Mining**	**Cement/Lime**	**Iron & Steel**	**Smelting**	**Pulp & Paper**
All feedbacks	NA	3.00	3.00	-0.23	2.22	-3.00
Energy feedbacks	NA	3.00	3.00	-0.22	2.19	-3.00
No feedbacks	NA	3.00	3.00	-0.20	1.85	3.00
Share of energy ($)	NA	6.34%	9.42%	31.38%	6.34%	7.92%
"	NA	6.37%	9.37%	32.24%	6.37%	7.42%
"	NA	6.34%	9.39%	31.54%	6.34%	7.89%

Other	**Manufacturing**	**Commerce**	**Residential**	**Transportation**
All feedbacks	3.00	NA	NA	NA
Energy feedbacks	3.00	NA	NA	NA
No feedbacks	3.00	NA	NA	NA
Share of energy ($)	22.79%	NA	NA	NA
"	22.15%	NA	NA	NA
"	22.75%	NA	NA	NA

Supply Models	**Coal Mining**	**Electricity**	**Natural Gas**	**Crude Ext.**	**Pet. Refining**
All feedbacks	0.61	NA	NA	NA	NA
Energy feedbacks	0.56	NA	NA	NA	NA
No feedbacks	0.56	NA	NA	NA	NA
Share of energy ($)	7.06%	NA	NA	NA	NA
"	7.16%	NA	NA	NA	NA
"	7.04%	NA	NA	NA	NA

All Canada	**Total all**	**Energy $(000's)**
All feedbacks	1.29	1,124,944
Energy feedbacks	1.29	1,102,306
No feedbacks	1.75	1,127,263

Table 51 National own-price elasticity for electricity by sector

Demand Models - Industry

	Chemicals	Mining	Cement/Lime	Iron & Steel	Metal Smelting	Pulp & Paper
Macro On	-0.35	-1.54	-0.54	-1.39	-0.13	-1.38
Macro Off	-0.32	-1.61	-0.72	-0.58	-0.16	-0.65
No feedbacks	-0.32	-1.60	-0.72	-0.60	-0.17	-0.65
Share of energy ($)	3.38%	3.87%	0.37%	1.12%	3.87%	6.86%
"	3.34%	3.82%	0.36%	1.12%	3.82%	7.05%
"	3.32%	3.81%	0.36%	1.11%	3.81%	7.03%

Other	Manufacturing	Commerce	Residential	Transport
All feedbacks	-0.48	-2.31	-2.66	-2.77
Energy feedbacks	-0.48	-1.98	-2.67	-1.87
No feedbacks	-0.48	-2.03	-2.57	-2.54
Share of energy ($)	6.35%	27.34%	40.65%	0.24%
"	6.27%	27.42%	40.47%	0.24%
"	6.25%	27.30%	40.66%	0.23%

Supply Models	Coal	Elec	NG	Crude	Refining
All feedbacks	-2.83	NA	-0.26	-0.74	-2.11
Energy feedbacks	-2.82	NA	-0.19	-0.73	-1.95
No feedbacks	-2.84	NA	-0.17	-0.74	-1.99
Share of energy ($)	0.13%	NA	5.38%	2.18%	0.25%
"	0.13%	NA	5.37%	2.28%	0.24%
"	0.12%	NA	5.41%	2.27%	0.25%

All Canada	Total all		Energy $(000's)
All feedbacks	-1.95		$32,718,127
Energy feedbacks	-1.79		$33,079,383
No feedbacks	-1.77		$33,081,754

Table 52 National own-price elasticity for natural gas by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	-1.36	-1.65	NA	-2.26	-2.25	-2.16
Energy feedbacks	-1.23	-1.39	NA	-2.27	-2.26	-2.16
No feedbacks	-1.34	-1.39	NA	-2.29	-2.31	-2.63
Share of energy ($)	3.23%	1.22%	NA	1.82%	1.22%	3.14%
"	3.21%	1.21%	NA	1.80%	1.21%	3.24%
"	3.22%	1.21%	NA	1.82%	1.21%	3.12%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	-1.53	-3.00	-2.77	-2.68
Energy feedbacks	-1.50	-3.00	-2.77	-2.65
No feedbacks	-1.56	-3.00	-2.79	-2.18
Share of energy ($)	7.45%	10.86%	25.91%	0.54%
"	7.39%	10.87%	26.06%	0.53%
"	7.38%	10.87%	25.66%	0.53%

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	-2.27	-0.99	-0.13	-0.34	-2.28
Energy feedbacks	-2.30	-0.86	-0.06	-0.28	-2.35
No feedbacks	-2.30	-1.01	-0.07	-0.35	-2.29
Share of energy ($)	0.11%	25.52%	10.57%	7.70%	1.46%
"	0.11%	25.37%	10.44%	7.81%	1.49%
"	0.11%	25.34%	10.74%	8.05%	1.48%

All Canada	Total all	Energy $(000's)
All feedbacks	-1.69	17,295,454
Energy feedbacks	-1.64	17,654,989
No feedbacks	-1.70	17,430,946

Table 53 National own-price elasticity for RPPs by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	-3.00	-2.81	-3.00	-1.80	-2.66	-2.27
Energy feedbacks	-3.00	-2.81	-3.00	-1.80	-2.95	-2.24
No feedbacks	-3.00	-2.81	-3.00	-1.80	-3.00	-2.26
Share of energy ($)	0.13%	0.10%	0.11%	0.05%	0.10%	1.31%
"	0.12%	0.09%	0.11%	0.05%	0.09%	1.30%
"	0.13%	0.10%	0.11%	0.05%	0.10%	1.33%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	-3.00	-3.00	-3.00	-0.10
Energy feedbacks	-3.00	-3.00	-3.00	-0.10
No feedbacks	-3.00	-3.00	-3.00	-0.10
Share of energy ($)	0.63%	2.35%	2.84%	90.81%
"	0.61%	2.35%	2.86%	90.83%
"	0.63%	2.37%	2.84%	90.76%

Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	-3.00	-2.49	NA	-2.99	-2.70
Energy feedbacks	-3.00	-2.44	NA	-2.98	-2.68
No feedbacks	-3.00	-2.50	NA	-2.99	-2.68
Share of energy ($)	0.13%	0.33%	NA	0.32%	0.26%
"	0.13%	0.33%	NA	0.33%	0.25%
"	0.13%	0.34%	NA	0.33%	0.25%

All Canada	Total all	Total w/o Trans	Energy $(000's)
All feedbacks	-0.35	-2.74	54,468,430
Energy feedbacks	-0.35	-2.84	54,469,699
No feedbacks	-0.36	-2.85	54,633,942

Table 54 National own-price elasticity for coal by sector

Demand Models

Industry	Chemicals	Mining	Cement/Lime	Iron & Steel	Smelting	Pulp & Paper
All feedbacks	-0.67	-2.98	-3.00	-0.09	-2.26	-3.00
Energy feedbacks	-0.77	-2.98	-3.00	-0.25	-2.28	-3.00
No feedbacks	-1.72	-2.98	-3.00	-0.25	-2.29	-3.00
Share of energy ($)	0.03%	2.24%	3.24%	21.41%	2.24%	0.00%
"	0.03%	2.22%	3.24%	21.48%	2.22%	0.00%
"	0.03%	2.25%	3.25%	21.64%	2.25%	0.00%

Other	Manufacturing	Commerce	Residential	Transportation
All feedbacks	-2.63	0.00	0.00	0.00
Energy feedbacks	-2.63	0.00	0.00	0.00
No feedbacks	-2.63	0.00	0.00	0.00
Share of energy ($)	0.05%	0.00%	0.00%	0.00%
"	0.05%	0.00%	0.00%	0.00%
"	0.05%	0.00%	0.00%	0.00%

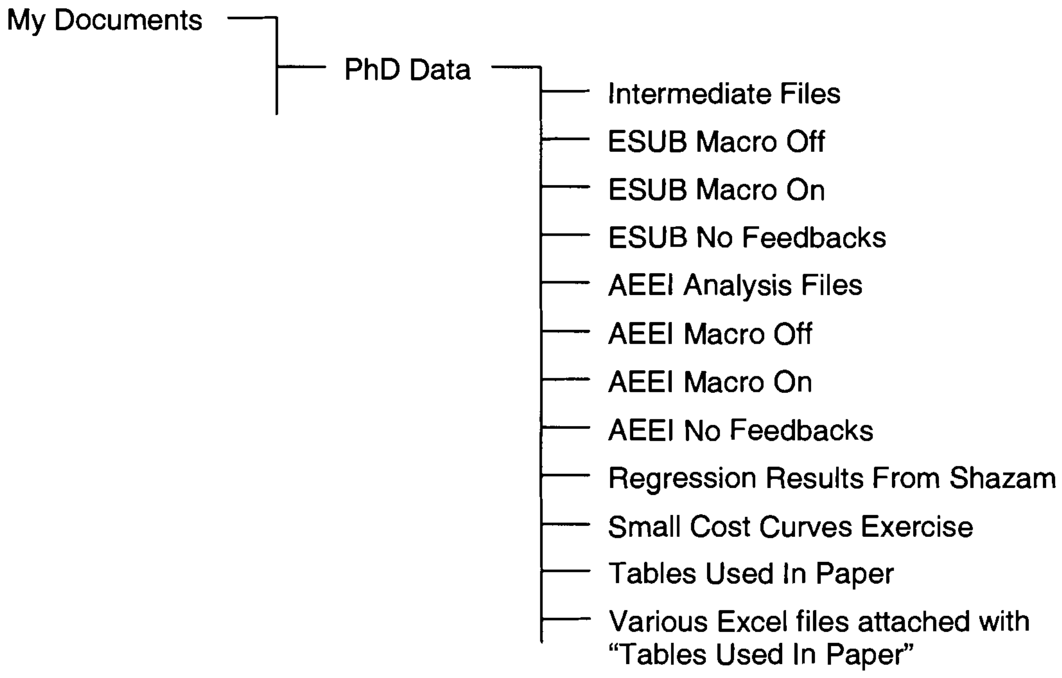
Supply Models	Coal Mining	Electricity	Natural Gas	Crude Ext.	Pet. Refining
All feedbacks	-3.00	-1.34	NA	0.00	0.00
Energy feedbacks	-3.00	-2.66	NA	0.00	0.00
No feedbacks	-3.00	-1.42	NA	0.00	0.00
Share of energy ($)	0.78%	72.18%	NA	0.00%	0.00%
"	0.78%	72.12%	NA	0.00%	0.00%
"	0.79%	71.92%	NA	0.00%	0.00%

All Canada	Total all	Energy $(000's)
All feedbacks	-1.16	1,517,096
Energy feedbacks	-2.15	1,522,964
No feedbacks	-1.25	1,511,781

Appendix H: CD-ROM appendix with detailed AEEI and ESUB calculations and regression results

Two CD-ROMs are included in the back cover of this thesis. They include all the detailed AEEI and ESUB run data and analysis files, including the regression results required for the ESUB calculation. The contents of the CDs are listed on the following page; for all links to work properly, extract the zip files using the following map.

Figure 28 Map to be followed in unzipping data and analysis files



Disc 1:

- AEEI Run and Analysis Files (zip file)
    - AEEI Analysis Files (folder)
    - AEEI Macro Off (folder containing run data)
    - AEEI Macro On (folder containing run data)
    - AEEI No Feedbacks (folder containing run data)
- ESUB Macro Off (zip file)
    - ESUB Macro Off (folder containing run data)
- ESUB No Feedbacks (zip file)
    - ESUB No Feedbacks (folder containing run data)
- Regression results from Shazam (zip file)
    - Regression results from Shazam (folder containing Word documents with regression for each region/sector pair)
- Inter-fuel Analysis Sheets and Tables (zip file)
    - Table used in Paper (folder containing analysis files)
    - Inter-fuel Analysis Sheets (Excel files)
- Intermediate Files (zip file)
    - Files used to transfer data from SHAZAM to Excel

Disc 2:

- ESUB Macro On (zip file)
    - ESUB Macro On (folder containing run data)
    - Primary ESUB analysis files are contained in ESUB Macro On
- Small Cost Curves Exercise (zip file)
    - Small Cost Curves Exercise (folder containing run data and analysis files)