MODELING CLIMATE POLICY: ADDRESSING THE CHALLENGES OF POLICY EFFECTIVENESS AND POLITICAL ACCEPTABILITY

by

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Abstract

Reducing greenhouse gas emissions by a substantial amount will require aggressive climate change policies. Policy makers and the public are concerned that such policies could be associated with negative economic impacts, such as reduction in the growth rate of economic output, loss of international competitiveness, and concentration of costs amongst vulnerable demographic groups, regions, or economic sectors. The aim of this thesis is to show that the design of climate change policy has a substantial bearing on such economic impacts, to the extent that policy makers can effectively choose many of the likely economic impacts of a particular climate change policy through careful design. Conversely, inattention during climate change policy design can lead to undesirable economic impacts.

The analysis is conducted with a series of computable general equilibrium models as well as an econometric model. These models are applied to examine both proposed and existing climate change and energy efficiency policies. Several findings emerge from the analysis. First, so-called 'intensity-based' climate change policies, which have been proposed in Canada for nearly a decade but which have met with much criticism, may be useful in promoting economic growth and maintaining international competitiveness. Second, under unilateral application of climate change policy, the international competitiveness of energy-intensive industries in developed countries is likely to be worsened. However, several policy mechanisms are available that substantially mitigate this loss in international competitiveness. Third, climate change policies are unlikely to result in a more unequal distribution of income in society, unless revenues from the policy are allocated in a equality-worsening manner. And fourth, past energy efficiency subsidies on average do not appear to have been cost-effective in reducing energy consumption.

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Introduction

1.1 The climate change challenge

Reduction of greenhouse gas (GHG) emissions to mitigate global climate change has so far proven extremely challenging. Scientists have been aware of the climate change problem for over a century (Arrhenius, 1896), it has been a policy concern in developed countries since at least the 1960s (Tukey et al., 1965), and it has been an extremely active area of scientific and economic research and public debate since the early 1990s. To date, however, despite evidence that the environmental and economic impacts of unabated climate change are likely to be large (Pachauri, 2007; Stern et al., 2006), the overall scale of the mitigation effort has been small.

As a result of limited mitigation effort coupled with rapid economic expansion, the atmospheric concentration of carbon dioxide - the most important anthropogenic GHG - is now over 390 parts per million, which represents nearly a 40 percent increase from pre-industrial levels of around 280 parts per million (Forster et al., 2007). When other greenhouse gases are included, the total concentration of atmospheric GHGs, measured according to their carbon dioxide equivalent, is close to 450 parts per million (Stern et al., 2006). Emissions and atmospheric concentrations of greenhouse gases continue to grow very quickly (Canadell et al., 2007). As a result, it now appears that it will be a major challenge to constrain GHG concentrations in the atmosphere at lower than 550 parts per million of carbon dioxide equivalent, which has long been a symbolic target since it represents a doubling from pre-industrial concentrations (Weaver et al., 2007). Such a target would entail dramatically cutting emissions over the coming decades, during a period where emissions are expected to increase quickly as a result of strong economic growth in developing countries (Barker et al., 2007).

A failure to dramatically cut emissions could be associated with potentially serious damages. The best estimate from the Intergovernmental Panel on Climate Change (IPCC) suggests that if even if the atmospheric concentration of greenhouse gases is stabilized at 550 parts of carbon dioxide equivalent per million, temperatures would still increase by about 3 ^oC relative to the pre-industrial average. With a temperature increase of this magnitude, models suggest that 20 to 40 percent of terrestrial species would likely be committed to extinction, coral mortality would be widespread, hundreds of millions of additional people would be exposed to increased water stress and malnutrition, and up to 30 percent of coastal wetlands would be lost (Parry et al., 2007).

However, the best estimate hides the substantial uncertainty underlying the projection. The IPCC is only about 60 percent confident that the temperature increase associated with a doubling of atmospheric carbon dioxide concentrations would fall in the range of 2 to 4.5 ^oC (Hegerl et al., 2007), and temperature increases as high as 7 and even 10 ^oC are even considered possible, with probabilities of around 5 percent and 1 percent, respectively (Weitzman, 2009). On the timescale of millennia, when long-term feedbacks have time to amplify the warming signal of GHG emissions, temperature increases might be even higher (Hansen et al., 2008). In this timescale there is a 5 percent probability that temperatures might increase by as much as 12 ^oC and a 1 percent probability of a 22 ^oC increase as a result of atmospheric GHG concentrations of 550 parts per million (Hansen et al., 2008; Hegerl et al., 2007; Weitzman, 2009).

While there is a vigorous debate about the potential economic impact of a 2 to 3 ^oC increase in global mean temperature (Stern et al., 2006; Tol, 2005), there can be little doubt that a double-digit increase in global mean temperature would have significant adverse economic and ecological impacts. Weitzman (2009) describes such temperature change as follows:

> Because these hypothetical temperature changes would be geologically instantaneous, they would effectively destroy planet Earth as we know it. At a minimum such temperatures would trigger mass species extinctions and biosphere ecosystem disintegration matching or exceeding the immense planetary die-

> offs associated in Earth's history with a handful of previous geo-environmental mega-catastrophes. There exist some truly terrifying consequences of mean temperature increases of 11 to 20^{o}C, such as: disintegration of the Greenland and at least the Western part of the Antarctic ice sheets with dramatic raising of sea level by perhaps 30 meters or so, critically-important changes in ocean heat transport systems associated with thermohaline circulations, complete disruption of weather, moisture and precipitation patterns at every planetary scale, highly consequential geographic changes in freshwater availability, regional desertification - and so forth and so on.

Even with a substantial mitigation effort in which emissions are contained at 550 parts per million, there are substantial risks of catastrophic warming. And because the environmental response to increased concentrations of greenhouse gas emissions is possibly non-linear, atmospheric concentrations above 550 parts per million could associated with much more severe impacts than those listed above. In short, the threat of climate change is real and severe. It has been called 'the greatest challenge facing the world' by (among many others) leaders as diverse as Ban Ki-moon, the Secretary General of the United Nations, Gordon Brown and Kevin Rudd, the former British and Australian Prime Ministers, and Stephen Chu, the current US Energy Secretary.

1.2 Economics of mitigation

Like most other environmental problems, the problem of climate change is at its root a problem of externality: those who engage in activities that produce GHG emissions do not bear the full cost of those emissions. As a result, the private cost of emitting activities is lower than the social cost of those activities, resulting in higher levels of the emitting activities and more emissions than is socially optimal.

The basic economic theory describing the optimal policy response to an environmental externality is well established. Assuming that the total social benefits of abating pollution are given by $B(a)$, where a is the quantity of emissions reduced from some benchmark level, and that the cost of reducing emissions is given by $C(a)$, then the social surplus from reducing emissions is given by $\pi = B(a) - C(a)$.[1] The first-order condition, $B'(a^*) = C'(a^*)$, suggests that this social surplus is maximized when the level of emissions abatement reaches a^*, such that the marginal benefit of abatement is set equal to its marginal cost.

Although a decentralized (free market) economy is unlikely to reach the efficient level of abatement on its own, government policy can be used to ensure that this condition is reached.[2] For example, by implementing an emission tax set equal to the marginal benefit of emissions abatement at a^*, the social damage from pollution is 'internalized' to polluters, removing the discrepancy between private and social costs described above. Such a policy should increase social well-being from the decentralized equilibrium (provided administrative and other costs associated with the policy are negligible).

Policy-makers may not always (or even often) choose environmental policies by weighing marginal costs against benefits of emission reductions explicitly, but the framework described here can still help to clarify the implicit cost-benefit calculus that takes place in the offices of policy makers.[3] Further, it helps to clarify the many successes that governments have recorded in reducing pollution emissions, especially in developed countries, for pollutants as diverse as sulfur dioxide, lead, mercury, noise, and dioxins. For each of these pollutants, policy makers have concluded that marginal benefits of abatement exceeded marginal costs of abatement at the free-market equilibrium, and so implemented policies to reduce emissions.

However, in the case of climate change, implementation of policies to internalize the external damages from emissions becomes substantially more complicated. When released by an emitter, greenhouse gases are resident in the atmosphere for long enough that they become evenly mixed. As a result, unlike for local or regional pollutants, the incremental impact of a tonne of greenhouse gas emissions is independent of the location in which

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[1] I assume that $B(a) > 0$, $C(a) > 0$, $B'(a) > 0$, $C'(a) > 0$, $C''(a) > 0$, and $B''(a) < 0$ for positive a.

[2] In a hypothetical setting with zero transaction costs between the emitter of pollution and the party that suffers damage, as well as clearly defined property rights, no government intervention is required for the economy to reach the optimal level of emissions abatement on its own (Coase, 1960). However, in the case of climate change, transaction costs are likely very high because of the large number of emitters and affected, and property rights over the atmosphere are ill-defined, necessitating a government response.

[3] In some cases, the framework is applied explicitly. For example, Under President Clinton, the US government began requiring that all 'major' new regulations, defined as costing at least \$100 million, should be screened using a formal cost benefit analysis prior to implementation.

it is released. Greenhouse gases have consequently been termed a global pollutant, and this physical characteristic has an important bearing on the policy calculus determining the optimal response of a policy maker at the level of a nation state, region, or municipality.

A simple model helps to illustrate. Consider N identical countries indexed by $i, j = 1..N$, each of which faces a cost of abatement given by $C_i(a_i)$, where a_i is the amount of abatement pursued by country i. The benefit of abatement in each country depends on the total abatement in all countries, because of the global nature of the pollutant, and is given by $B_i\left(\frac{a_i+\sum_j a_j}{N}\right)$, where $j \neq i$. The global social surplus is given by $\pi = N \cdot B_i\left(\frac{a_i+\sum_j a_j}{N}\right) - C_i(a_i) - (N-1)C_j(a_j)$, and is maximized when $B_i' = C_i'$, as above. In words, this implies that a global social optimum is reached when the global marginal benefit of abatement is equal to the marginal cost of abatement in an individual country. A global social planner would choose this level of abatement for each country.

However, no single global decision maker exists. Instead, environmental policies are typically set at the level of national governments (or at a sub-national level, depending on the country), and each country can be assumed to consider the benefits and costs of a policy to its own citizens, not the entire globe. Such a decision maker would be aiming to maximize social surplus for the country, given by $\pi_i = B_i\left(\frac{a_i+\sum_j a_j}{N}\right) - C_i(a_i)$, which results in the first order condition $\frac{1}{N}B_i' = C_i'$. In words, with national policy makers and a global pollutant, each country is only willing to reduce emissions to the point where the national marginal benefit from emission reductions is equal to its marginal cost. With a large number of countries, this means that the amount of abatement chosen by national policy makers is substantially below the global social optimum. Since the world is divided up into around 200 countries, this simple framework helps to explain why most countries have engaged in very little emissions abatement: each country prefers to free-ride on the efforts of others, sharing in benefits of emissions abatement but not in the costs.

This treatment of the climate change problem corresponds to the definition of a public good given by Samuelson (1954, 1955) , and has led Nordhaus (1993) to refer to climate change as “the granddaddy of all public goods problems”. It is this global dimension of the climate change problem that explains the substantial effort that the international community is currently investing to develop an international agreement to limit global warming, and that also explains the relatively limited abatement effort that has been pursued by most regions in the absence of such an agreement.

Securing a meaningful and stable international agreement to reduce greenhouse gas emissions has and will continue to present a major challenge. As Barrett (2005) explains, such an agreement must be ‘self-enforcing’, such that membership in the agreement is sustained by the incentives facing individual nations. In a self-enforcing agreement, a participating nation will not withdraw from an agreement because the costs associated with withdrawal exceed the costs of remaining a party to the agreement. For climate change, where costs of reducing emissions are likely to be relatively high, and where benefits from reducing emissions are spread throughout the many countries of the world, Barrett (2005) shows that a self-enforcing agreement is particularly hard to achieve.

Despite sharing with Barrett (2005) an overall pessimism about the near-term likelihood of success of a formal international environmental agreement, Ostrom (2009) is optimistic that states may work together informally to improve on the non-cooperative outcome. Based on extensive review of small- and medium-scale natural resource case studies where participants face similar incentives as nation-states in managing the global atmosphere, she find that cooperation often ensues (in contradiction to the standard economic theory described above) when participants can communicate, monitor one another, and reciprocate actions over a long time horizon. Early efforts by local, regional, and state governments to reduce climate change reinforce her conclusion that more substantial cooperation may emerge, even in the absence of a formal agreement.

Whether a formal international agreement to govern the climate is reached, or whether cooperation emerges from a gradual building of trust amongst nation states taking reciprocal actions, success at tackling climate change will ultimately require the design and implementation of mitigation policies at a national and sub-national level, since almost no analysts take seriously the possibility of a supra-national coercive governing body with the power to levy taxes and otherwise regulate emissions. While there exists a substantial body of experience with the implementation of environmental policies at national and sub-national levels, there remain substantial challenges associated with deep reductions of domestic greenhouse gases. This thesis is an exploration of such policies, focusing in particular on how the careful design of market-based climate change policies can address issues of particular concern associated with the application of domestic policy. Much of the quantitative analysis focuses on Canada, although the issues addressed are broadly similar for other developed countries.

1.3 Market-based climate policies

Since the 1970s, policy-makers aiming to reduce pollution have relied primarily on command and control policies.[4] Such policies typically prescribe particular technologies that should be used by all regulated entities (for example, a minimum efficiency standard for refrigerators requires all new refrigerators to reach some minimum level of efficiency) or require all regulated entities to take on a similar share of the pollution reduction burden (for example, through a performance standard that requires a minimum heat rate for thermal electricity generators). Importantly, these command and control regulations allow little or no flexibility in the means of achieving goals.

Requiring all entities to take on a similar share of the pollution reduction burden or to adopt identical technologies can be an effective method to reduce pollution, but has the potential to be expensive. In particular, the lack of flexibility associated with a command and control regulation means that some entities will be required to undertake abatement investments with especially high marginal costs, while other entities will pass up investments that could reduce pollution with very low marginal costs. Additionally, although command and control regulations impose an additional cost on a firm associated with installing and maintaining new technology, they do not impose any financial penalty on emissions that remain after the new technology is installed. As a result, the level of output is inefficiently high when a command and control standard is applied. In a seminal study of the costs of environmental policies, Tietenberg (1985) concluded that because of these characteristics, command and control regulations actually in place have cost up to 22 times more than a hypothetical least-cost benchmark (in which all firms abate pollution to the point where marginal costs are equalized and consumers receive appropriate price signals).

While command and control regulations are still widely used to provide environmental protection, their potentially high cost has led to a surge of interest in market-based policies for environmental protection. For example, Aldy et al. (2010) claim that: “Debate over the choice of instrument for a nationwide carbon control program is no longer about the superiority of market-based approaches over traditional forms of regulation (like technology mandates) but rather between market-based alternatives”.

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[4] I focus only on mandatory policies in this thesis; voluntary programs, including information disclosure programs, and not addressed here.

Using a market-based environmental policy, a regulator provides incentives for firms and households to reduce emissions, but provides substantial flexibility in how (i.e., what technologies are used to reduce emissions) and where (i.e., what entities reduce emissions) emission reductions actually take place. For example, by implementing a tax on emissions, the regulator ensures that firms will reduce emissions to the point where the marginal cost of emissions reductions is equal to the tax amongst all regulated firms and amongst different activities within each firm. Firms that have few opportunities for pollution abatement will undertake relatively few investments in abatement, choosing instead to pay the tax and keep emitting, while firms that have a wide scope for low-cost pollution abatement will undertake a larger quantity of emissions abatement. This flexibility can be associated with dramatic cost savings relative to command and control policies, since it encourages emissions abatement to take place where costs are lowest using the most cost-effective technologies (Stavins, 2001). Additionally, both the cost of emission control, as well as the cost associated with remaining emissions, are reflected in the product price, giving the final consumer the appropriate signal regarding the quantity of output to consume.

In addition to these potentially large cost savings from allocating pollution abatement investments to their most effective use, market-based strategies for environmental protection are likely to encourage increased development of new technologies for reducing pollution compared to command and control regulations. While command and control regulations freeze the level of technology at the level embodied in the regulation and provide no incentive for the development of new technologies that exceed the regulatory stringency, market-based policies provide a continual incentive for firms to develop new pollution abatement technologies, since new abatement technologies reduce a firm's total costs (and increase profits) at any level of pollution (Milliman and Prince, 1989; Fischer et al., 2003). Because many environmental problems, and most notably climate change, have an extremely long time horizon, development of new technologies may be critical. As Jaffe and Stavins (1995) put it:

> In the long run, the development and widespread adoption of new technologies can greatly ameliorate what, in the short run, sometimes appears to be overwhelming conflicts between economic well-being and environmental quality.

1.3.1 Market based climate policies in Canada

Using a variety of types of energy-economy models, researchers have explored the likely stringency of market-based climate change policy that would be required to meet a given level of emissions reduction in Canada. Since such policies generally involve an explicit price on emissions, a natural measure of policy stringency is in dollars per tonne of carbon dioxide (\$/t CO_2). Figure 1.1 is a collection of model results from many such studies where some effort was made to normalize results from across model types to account for differences in scenario definitions, timeframes, and prices. Although there is some disagreement between various models, the general conclusion is that relatively stringent policies are required to meet the type of emission reduction targets that are the subject of political and scientific discussion (a 25 to 50 percent cut in emissions), and that the required stringency of policy increases exponentially with respect to the level of emission reductions. For example, a 25 percent reduction of emissions from business as usual levels over 10 years might require implementation of a market-based policy with a marginal price of roughly \$50 to \$100/t CO_2, while reduction by 50 percent might require a policy with a marginal price of around \$250/t CO_2 or more, five times as high.

There are several potential effects that could be associated with market-based policies of this stringency that cause concern for some Canadians. The first, and perhaps most important, concern is that stringent greenhouse gas reduction policies could cause contraction of the overall economy. Reduction in gross domestic product is a concern primarily since it reflects a diminished final consumption stream. As a rough proxy, the level of gross domestic product reflects the level of economic welfare in society (although there are many well-known problems with this measure). Transitional impacts associated with reduction in economic output are also concerning. Perhaps most importantly, the empirically-established link between the rate of growth of economic output and the rate of unemployment suggests that a reduction in the former is likely to be associated with an increase in the latter. Policy makers are generally extremely averse to policies that are likely to increase the rate of unemployment, for obvious reasons.

One of the key outputs of existing modeling studies, such as those reported in Figure 1.1, is the impact of the policy on economic output. As with the estimates of policy stringency required to achieve a given target, there is a range of estimates projecting the

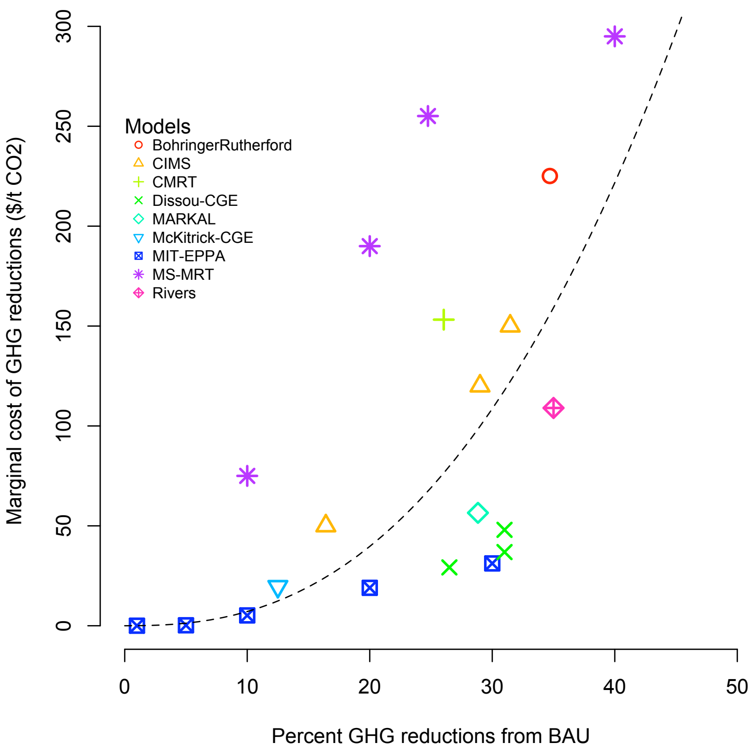

Figure 1.1: Stringency of market-based climate change policies in Canada. All studies use approximately a 10-year time horizon between policy implementation and reporting of greenhouse gas emission reductions. Where applicable, all studies recycle revenue collected from application of market-based policy in lump sum to households. The dashed line is a regression line through unweighted model results of the form $MC = a \cdot R^b$ where MC is marginal cost and R is percent reductions. Prices are in 2002 Canadian dollars. Model types referred to in the Figure are discussed in Chapter 3.

economic cost of meeting a greenhouse gas reduction target. However, as shown in Figure 1.2, to reduce emissions by a 25 percent from business as usual levels over a period of 10 years, models typically project a reduction in the level of gross domestic product of between 1 and 2 percent.[5] Although this reduction is relatively small, it is large enough

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[5] This variable is strongly affected by the design of the climate policy. The studies reported in Figure 1.2

to merit legitimate concern by policy makers and by the public for the reasons described above.

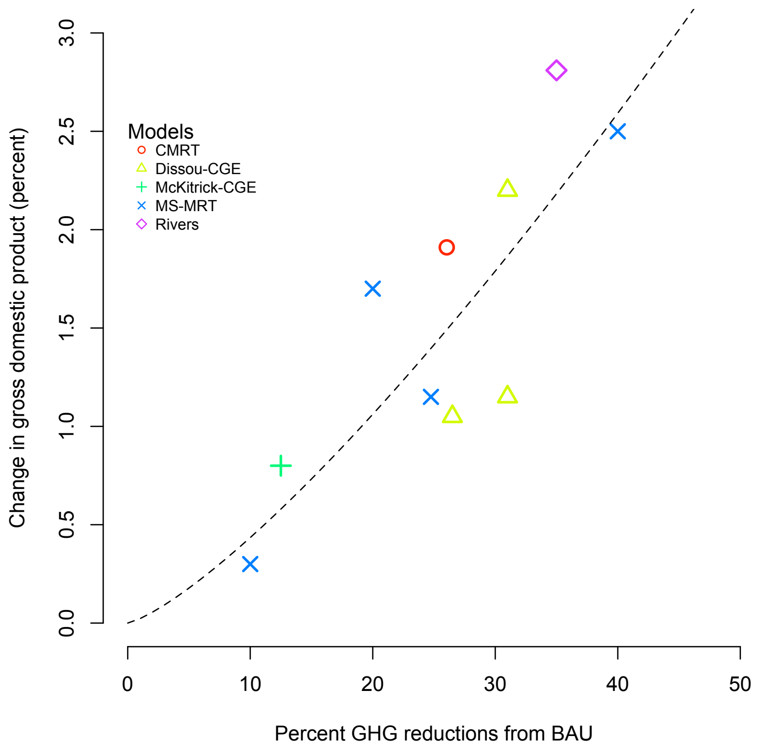

Figure 1.2: GDP cost of market-based climate change policies in Canada. All studies use approximately a 10-year time horizon between policy implementation and reporting of greenhouse gas emission reductions. Where applicable, all studies recycle revenue collected from application of market-based policy in lump sum to households. The dashed line is a regression line through unweighted model results of the form $GDP = c \cdot R^d$ where GDP is the GDP cost and R is percent reductions. Model types referred to in the Figure are discussed in Chapter 3.

In addition to impacts on overall economic output and associated employment impacts,

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use a uniform carbon tax with lump sum revenue recycling to households. Other market-based policy designs are likely to yield different GDP costs.

a major concern is over the potential loss of international industry competitiveness that might accompany implementation of a domestic climate change policy. Since most market-based greenhouse gas policies are likely to increase costs of industry production, a natural concern is that some firms are likely to shed market share to foreign competitors following implementation of a domestic climate policy. This loss in competitiveness has the potential to reduce domestic wages, increase unemployment, and reduce overall economic output. Additionally, when firms move out of a jurisdiction to avoid regulation, they may leave emissions unchanged (or even increase emissions) if the new jurisdiction has lax environmental policies, such that the original goal of reducing emissions can be missed. This phenomenon has become known as emission 'leakage'.[6] Leakage and competitiveness are concerns in all countries, but are perhaps particularly acute concerns in Canada, which is very tightly integrated with the world economy through international trade, and which contains a high concentration of energy-intensive firms.

There have been a number of studies that attempt to determine the degree to which these concerns are warranted. Most of these find that emissions 'leakage' is probably around 15 to 25 percent, so that companies shifting across jurisdictions to avoid environmental regulation is unlikely to substantially reduce the effectiveness of domestic climate policy (Felder and Rutherford, 1993). However, relatively few studies have been conducted to determine the losses in employment and economic output that might accompany changes in international competitiveness following implementation of a climate change policy.

Another major concern associated with implementation of stringent climate change policies is that the burden of such policies could be concentrated within certain groups, rather than spread evenly throughout the population. When the impact of a policy is concentrated in a certain group, it is more likely to generate opposition, and might be considered less fair. Distributional concerns have emerged along several dimensions. First, since different regions within a country can have quite different greenhouse gas emission profiles, there has been concern that some regions will bear a disproportionate burden from federal market-based climate change policy (Peters et al., 2010; Snoddon and Wigle, 2007). Sec-

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[6] Leakage is formally defined as the increase in foreign emissions resulting from the policy divided by the decrease in domestic emissions. For example, if prior to policy implementation, domestic and foreign emissions are 100 and 1,000 units respectively, and following the implementation of domestic policy emissions are 50 and 1,005 units respectively, the leakage rate is $L = \frac{5}{50} = 10\%$.

ond, as with different regions, different economic sectors have very different greenhouse gas intensities. As a result, it is not surprising that industry sectors with high greenhouse gas intensity have been substantially involved in the debate over climate change policy. Third, concern has emerged that climate change policy could affect certain income and demographic groups, including rural, low-income, and elderly segments of the population.

These concerns have slowed the implementation of climate change policy in Canada as well as in other developed countries. Addressing these concerns is probably an important precursor to the passage of meaningful domestic climate change policies. Fortunately, it is likely that there are mechanisms that make this possible. In particular, although they all share certain characteristics described above, market-based environmental policies are not homogeneous. Different policy designs can result in substantially different incentives, allocation of burden, and overall cost. Appropriate choice of market-based policy can therefore help to mitigate some of the effects that are of particular concern to Canadians.

To capture the heterogeneity that exists within market-based climate change policies, I begin by describing a general taxonomy of such instruments:

Pollution charges or pollution taxes require that emitters pay a fixed fee for every unit of emissions released into the environment. As a result, cost-minimizing polluters will undertake emissions abatement up to the point where the marginal cost of abatement is exactly equal to the pollution charge. If the pollution charge is set equal to the marginal social benefit from pollution reduction, such a system should result in a socially optimal level of abatement. However, since the regulator does not know *ex ante* the (marginal) abatement costs for all polluters, it cannot know with certainty what level of pollution will result from the application of any particular level of tax (Weitzman, 1974). Depending on the level of the charge and the quantity of emissions covered, a pollution charge can raise a substantial amount of revenue for the regulator. Prominent examples of pollution charges include carbon taxes implemented by British Columbia, Quebec, and many of the Northern European countries. Pollution taxes have also been used for a wide array of local air pollutants, especially in Europe (Stavins, 2001).

Emissions cap and tradable permit schemes implement an overall cap on emissions from a sector of the economy (or the entire economy) and allocate permits equal to the size of the overall cap to emitters covered by the scheme. Permits are tradable between firms, such that firms that are allocated permits in excess of their requirements are able to sell them to other firms. Through this trading process, permits acquire a market value, which provides a similar abatement signal as a pollution charge. Unlike with a pollution charge, the regulator knows *ex ante* the level of pollution that will result, but not the market price for tradable permits that will result (Weitzman, 1974). An important characteristic of an emissions cap and tradable permit scheme is that the allocation process allows substantial flexibility for the regulator to shift costs between regulated entities. The two most widely known examples of cap and trade systems are the Title IV amendments to the US Clean Air Act of 1990 that limit sulfur dioxide and nitrogen oxide emissions from large electricity generating and industrial facilities (Schmalensee et al., 1998; Stavins, 1998), and the European Emission Trading System, which limits carbon dioxide emissions from industrial facilities (Ellerman and Buchner, 2007; Convery et al., 2008).

Tradable emissions performance standard schemes involve a requirement that covered firms reach a level of emissions intensity (emissions per unit of output) set by the regulator. Firms that achieve an emissions intensity lower than required by the regulator obtain permits, and these permits can be sold to firms that fail to achieve their own required emission intensity limit. As such, the tradable emission performance standard shares characteristics with the emission cap and tradable permit system. However, unlike this system, under a tradable emissions performance standard, the regulator knows the emission intensity but not the overall level of emissions that will result. The province of Alberta has implemented a tradable emission performance standard to address carbon dioxide emissions, and such a standard was used by the US government in it's phase-out of lead from gasoline in the 1980s (Fischer, 2001).

Subsidies share some similar characteristics with pollution charges. By providing an incentive to adopt particular technologies or to reduce emissions, a subsidy can harness market forces in much the same way as a pollution charge. However, there are also a number of dissimilarities. While encouraging firms to undertake pollution abatement activities, a subsidy lowers a firm's average cost and so increases profits, resulting in new firms entering the market or existing firms increasing their activity level, both of

> which increase pollution (a similar effect is evident for consumer subsidies, whereby a subsidy can increase a consumer's demand for a particular service, even as the energy efficiency of that service is improved) (Kohn, 1992). Perhaps more importantly, when a regulator provides a subsidy it must set a performance benchmark beyond which a subsidy will be available (a level of pollution intensity or a particular technology). However, in setting the benchmark level, it faces a tension between setting it so high that no firms will be able to reach it, and setting it so low that many firms will exceed the benchmark even without the subsidy. Usually, the level is set such that some firms qualify for the subsidy without any change in behaviour. These are considered free-riders, and increase the cost of the subsidy without contributing to its effectiveness (the economic literature sometimes refers to the free-rider problem as an adverse selection problem, since the regulator lacks information to know which recipients require the subsidy to change behaviour, and which do not). Subsidies are widely used to promote environmental protection; recent examples include tax exemptions for hybrid vehicle purchases in Canada and the US (Chandra et al., 2010), and subsidies for improving electricity use efficiency (Loughran and Kulick, 2004).

Because they provide such different incentives, resulting in different costs and benefits to different individuals, careful choice from among these different types of market-based policies can have a large impact over the various potential impacts associated with climate policies. In some cases, it is possible to combine the features of two or more market-based policies to arrive at a policy design that more closely achieves desired results. Perhaps even more importantly, choice of the particular design attributes of climate change policy can have a large influence over its environmental effect and economic impacts. For example, choice of how permits are allocated in a cap and trade system is an important determinant of its effect. Likewise, choice of the parameters of an environmental subsidy (the level of the subsidy as well as the particular technologies subsidized) dictate the resulting effect of the policy. Through manipulation of these design elements, it is therefore possible to address (or worsen) the concerns raised above related to climate change policy.

This thesis is an exploration of how the choice of category of market based policy as well as its detailed design elements can be used to address the concerns described above, related to economic efficiency, distributional incidence, and competitiveness. The main finding of my thesis is that market-based policies can be chosen to have a wide range of impacts, which leaves substantial flexibility for policy makers to 'design-out' the effects of most concern. However, I also show that there are generally trade-offs associated with addressing particular concerns, where addressing one concern has the potential to exacerbate another. Nonetheless, it is critical for policy makers to recognize the substantial flexibility of market-based climate policies to achieve a given environmental target while avoiding certain undesirable economic impacts. The aim of this thesis is to aid in that understanding.

Chapter 2

Objective and structure of thesis

This thesis consists of four separate papers, all on the theme of greenhouse gas reduction or energy efficiency policy, and all with a focus on Canada. This section briefly introduces each of the papers, and provides a brief non-technical summary. The following section focuses on methodological issues associated with modeling climate change and energy policies. A concluding section draws insights from the assembled research, and includes a discussion of further research. Finally, each of the papers is included in full. The topics of the papers are listed below. Where papers are jointly authored, I list authorship as well as the contributions of each author. Because the papers were written as stand-alone papers, there is some repetition, especially in the methodology sections, of individual papers.

Papers using computable general equilibrium approach:

1. "Intensity-based climate change policies in Canada", joint with Mark Jaccard, published in *Canadian Public Policy*, 2010, 36(4). In this paper, I conceived of the study, I conducted the literature review, I developed the quantitative model and conducted the analysis, and I wrote the draft of the paper. Mark Jaccard reviewed several drafts of the paper and made substantive changes to the manuscript.

   During the past decade, governments in Canada have proposed several market-based climate change policies. Each of these has used an intensity-based approach, in which government mandates the emissions intensity and firms trade credits with one another to achieve the target in aggregate. The approach has been widely critiqued because it does not guarantee a future level of emissions, unlike a cap and trade system. However, this paper demonstrates that it may offer certain advantages with respect to maintaining international competitiveness of energy-intensive sectors, reducing negative economic impacts associated with tax interactions, and promoting technical change. The paper uses a dynamic computable general equilibrium model to numerically evaluate the performance of this approach compared to other approaches for implementing a market-based carbon policy. It finds some merit to the intensity-based approach, because it promotes overall economic output and reduces leakage of energy intensive industries to other countries.

2. "Impacts of climate change policy on the competitiveness of Canadian industry: How big and how to mitigate", published in *Energy Economics*, 2010, vol. 32(5), pp. 1092-1104.

   In this paper, I use a dynamic computable general equilibrium model to assess the degree to which Canadian firms are likely to suffer from reductions in international competitiveness as a result of the adoption of a unilateral carbon pricing policy. I find that producers of industrial chemicals, refined petroleum products, and agricultural products are likely to become less internationally competitive following imposition of a Canadian carbon price. I consider several alternative policies that could help to alleviate these concerns over competitiveness, including revenue recycling schemes, border tax adjustments, sector exemptions, and output-based rebating. I find that except for revenue recycling strategies, all of these are able to help mitigate the impacts of the policy on competitiveness of energy-intensive sectors. However, some of them, including sector exemptions and import tariffs, substantially increase economic costs, and some, including border tax adjustments, are likely to be controversial from a trade law perspective.

3. "Distributional incidence of climate change policy in Canada".

   In this paper, I am concerned with how the design of a climate change policy affects the distribution of income in society. I build a single-period general equilibrium model of Canada, and simulate alternative climate change policies, to help answer this question. The model shows that alternative climate policy designs have substantial influence on the distribution of income, with policies that rebate carbon pricing revenues in lump sum promoting a more equal distribution of income in society, and policies that use carbon pricing revenues to lower pre-existing income taxes promoting a less equal distribution, but a higher aggregate income. I examine the trade off between income and equality in climate change policy, and find that by reserving about 30 percent of all carbon pricing revenues for lump sum redistribution, government can maintain the level of income inequality unchanged. This strategy leaves the rest of the revenue available to promote other goals, such as improving efficiency or pursuing additional emission reductions. I also examine strengths and weaknesses of alternative modeling approaches to evaluating distributional incidence of climate policy. I find that input output methods, which assume fixed shares of inputs in production and consumption, provide misleading estimates of the distributional incidence of climate policies.

Papers using an econometric approach:

1. "Electric utility demand side management in Canada", joint with Mark Jaccard. Mark Jaccard and I jointly conceived of the idea for this paper, I conducted the literature review, I conducted the quantitative analysis, and I wrote the first draft of the paper. Mark Jaccard offered suggestions for improving the analysis, reviewed the manuscript several times, and provided context on regulatory environment for electric utilities in Canada. A research assistant (Jonn Axsen) collected much of the original data from utilities on demand side management expenditures, under my guidance.

   This paper sets out to econometrically estimate the effectiveness of electric utility demand side management (DSM) investments in Canada. By using data from all provinces in Canada, and treating DSM expenditures as a 'natural experiment', we are able to isolate the causal impact of these investments. The panel data we use allows us to capture the dynamic process by which electricity adjusts towards the desired level of consumption following a shock, and to address unobserved time-invariant heterogeneity that exists between provinces. Our analysis reveals estimates for the price and income elasticity of electricity demand that are consistent with other studies, but suggests that demand side management expenditures have had very little effect on electricity sales in Canada. We hypothesize that high levels of free-ridership as well as a rebound effect are likely reasons for this lack of effect.

Chapter 3

Modeling climate change policies

3.1 Introduction

Policy makers and analysts frequently use energy-economy models to assess the likely consequences of public policies on the energy system and the rest of the economy. Since the 1970s, when these models first started to be used, they have been developed in two primary streams, which have come to be known as top-down and bottom-up approaches to energy-economy modeling.

Bottom-up models are disaggregated models of the energy-economy that contain a detailed representation of current and emerging technologies that can be used to satisfy demands for energy services. Technologies are characterized in terms of capital and operating costs, as well as performance attributes such as fuel consumption and emissions profile. When their financial costs in different time periods are converted into present value using a social discount rate (opportunity cost of capital), many emerging technologies available for abating various emissions appear to be profitable or just slightly more expensive relative to existing stocks of equipment and buildings. Conventional bottom-up models suggest, therefore, that substantial environmental improvement related to energy use can be profitable or low cost if these low-emission technologies were to achieve market dominance. Typical examples of bottom-up models include the MARKAL set of models (Fishbone and Abilock, 1981) and the model recently used by the McKinsey consulting group to produce a greenhouse gas abatement cost curve for the United States (Enkvist et al., 2007).

Many economists criticize the conventional bottom-up approach, however, for its assumption that a simple financial cost estimate indicates the full social cost of technological change. New technologies present greater financial risks, as do the longer paybacks associated with irreversible investments such as most energy efficiency investments. Some low-cost, low-emission technologies are not perfect substitutes for their competitors, requiring a substantial, ongoing subsidy before businesses or consumers will adopt them. To the extent they ignore some of these costs, conventional bottom-up models may suggest the wrong technological options and the wrong policies (or policy intensities) for policy makers.

Another challenge with the conventional bottom-up approach is that its technology-specific focus hinders its ability to portray broader macroeconomic effects of policies, notably the trade and structural repercussions from changes in energy prices and costs throughout the economy. In this sense, conventional bottom-up models only provide a partial equilibrium analysis of the response to policies. Further, bottom-up models, which ignore consumer preferences, do not provide a useful estimate of a policy on the overall well-being of society, or of the well-being of individual members of society. This is obviously important for climate change policies, which could impose substantial changes to business as usual in a variety of markets.

Top-down analysis, which is usually applied by economists, estimates aggregate relationships between relative costs and market shares of energy and other inputs to the economy, and links these to sectoral and total output in a broader equilibrium framework. Elasticities of substitution indicate the substitutability between any pair of aggregate inputs (capital, labor, energy, materials) and between energy forms (coal, oil, gas, renewables) within the energy aggregate. Because these parameters can be estimated from real market behaviour, as prices and consumption of various commodities have changed historically, they are said to reveal the actual preferences of consumers and businesses, and therefore implicitly incorporate losses or gains in non-financial consumer welfare, as well as reflect the market heterogeneity of real-world financial cost conditions.

Top-down models can also be criticized however. The key parameters in conventional top-down models are usually estimated from historical data, or where that is not available, assigned judgmentally. Even if the confidence intervals of these estimated parameters are narrow, there is no guarantee that values derived from past experience will remain valid into the future (Grubb et al., 2002). For example, the elasticity of substitution could change dramatically in the future as financial costs of technologies change due to economies of scale in production or accumulated experience, and as consumers become more accepting of emerging technologies as these are established in the market (Axsen et al., 2009). Because top-down models typically use fixed parameters, these may not show the full adaptation of firms and households to policies that significantly affect economic conditions. This can in turn lead to high cost estimates for policies to abate energy-related emissions. Another problem for the top-down approach is that the constraints of policy development often push policy-makers towards technology- and building-specific policies in the form of tax credits, subsidies, regulations and information programs. With their abstract depiction of technological change, top-down models have considerable difficulty addressing some of questions that policy makers are interested in.

Efforts to combine the desirable features of top-down and bottom-up models are ongoing. For example, bottom-up modelers have begun a process of linking their depiction of the energy sector with the rest of the economy in order to capture feedbacks between sectors (Bataille et al., 2006). Likewise, these modelers have worked on more accurately depicting the process of consumer choice between technologies, in order to address the critique that these models do not correctly capture the nuances in consumer behaviour (Rivers and Jaccard, 2005; Horne et al., 2005). Similarly, top-down models have started to include representation of discrete technologies, especially in the energy supply sector (Bohringer, 1998). Neither of these efforts have produced a true ‘hybrid’ model, however, in the sense that no model completely incorporates all desired attributes of both top-down and bottom-up models. Bottom-up models continue to lack a full representation of feedbacks between energy and non-energy sectors of the economy as well as a realistic depiction of international trade or a foundation based on well-established economics of consumer and firm behaviour that is suitable for welfare analysis. Top-down models continue to lack technological detail in most sectors, and where it is included, technologies are typically assumed to be perfect substitutes for one another, which does not capture real-world dynamics.

As a result, there is no clearly superior modeling approach to choose for analysis of all types of climate policies. Rather, choice of model is contingent on the application. In this thesis, I am concerned with whole-economy reactions to environmental policies, trade impacts, as well as welfare analysis, and I do not focus on analysis of technology-specific policies. As a result, I have chosen to use a top-down approach for the analysis. The remainder of this chapter outlines the type of model that I have used in my thesis, and develops a simple model in an intuitive manner so that results later in the thesis can be better understood.

3.2 Computable general equilibrium models

3.2.1 Introduction

Computable general equilibrium (CGE) models represent an extension and practical application of standard ('neo-classical') microeconomic theory and are the main variant of 'top-down' model used in climate policy analysis. Since the 1980s, CGE models have become increasingly widely used, as a result of both increases in computing power and the development of specialized mathematical programming software that substantially eases implementation. CGE models can now be run on a personal computer, and are routinely used in the analysis of international trade, tax and public finance, economic development, and environmental policy.

A basic CGE model rests on the notion of the circular flow of income in society (Figure 3.1). In this representation, households are endowed with factors of production, which they rent to firms in return for income. Firms use these factors of production to produce goods, which are sold to households, and which generate revenue for the firms.[1][2]

In addition to representing the physical and monetary flows in the economy, Figure 3.1 implicitly captures the notion of equilibrium in the economy. Provided that there is no free disposal of commodities, all goods that are produced by firms must be consumed

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[1] In an applied CGE model, many firms would produce a variety of different outputs, using many different inputs, and a number of different agents would be specified, each of which might have different preferences for consumption and a different endowment of factors of production. For example, an obvious extension would involve separately specifying a government agent that collects taxes to finance redistribution and public good provision, and a foreign agent that supplies imports and absorbs exports.

[2] Ecological economists typically embed the 'circular flow' diagram within a broader environment, such that flows of raw materials from the environment, flows of residuals to the environment, and the use of environmental amenities are explicitly modeled. As my analysis in this thesis is strictly economic in nature, and since I typically analyze policies with identical environmental attributes, I omit this feature from the diagram here.

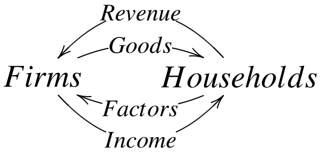

Figure 3.1: Circular flow in the economy

by households. That is, the physical quantity of goods that are produced must equal the physical quantity of goods that are consumed. Similarly, all factors with which households are endowed must be employed by firms; idle factors of production are not consistent with equilibrium.[3] This condition is the *market-clearance condition*, and in general terms it states that the total quantity supplied of any commodity in the economy must equal the total quantity demanded. In addition to this condition, the closed nature of Figure 3.1 suggests that the revenue earned by the firm due to its sales of goods to the household must be entirely spent by the firm on acquiring factors of production. That is, value must be conserved in the economic system - it cannot be created out of nothing and cannot disappear. This condition is otherwise knows as the *zero profit condition*, and applies to all firms in the economy. In a similar manner, the income of households must be entirely exhausted in purchasing goods from firms (some of which can be for the purpose of saving). This condition is known as the *budget balance condition*.

When all three of these conditions are met, for all markets, firms, and agents in the economy, respectively, the economy is said to be in general equilibrium. A CGE model exploits these three conditions (as will be shown later in this chapter) to solve for a set of prices and an allocation of resources that is consistent with general equilibrium.

The usefulness of a CGE model lies in its consistent, theory-based structure, and its ability to capture linkages between the various markets that are modeled. A policy that affects firms in one sector, for instance, will affect equilibrium in markets for the commodity produced by that sector as well as factors demanded by those firms. In turn, these changes in demand and output will cause cascading changes in other markets. Partial equilibrium approaches, which focus on a single market, miss these linkages, and therefore do not fully capture the impact of a policy.

Such general equilibrium impacts are likely of special importance in the analysis of

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[3] However, modifications to CGE models can and are made to account for idle factors of production, like unemployment in the labour market.

climate change policy. Greenhouse gas emissions are produced in virtually every economic activity in the economy. Further, the economic impacts of substantial market-based climate change policies on particular sectors can be substantial. Since impacts on a given sector can be transmitted both directly and indirectly to other sectors and to the various agents in the economy, a CGE approach can generate important insights that can be missed in a partial equilibrium model.

However, a CGE approach to analysis is associated with several disadvantages compared to other modeling approaches. I elaborate here on these criticisms, which were introduced in the previous section.

Arguably the key disadvantage of CGE models lies in the calibration procedure that is required.[4] First, the general form of functional relationships describing the preferences and technology of agents in the economy must be specified. Since most CGE models use restrictive functional forms, the process of choosing these limits the range of model results that can be obtained (McKitrick, 1998).[5] Once key functional relationships describing the behaviour of agents in the economy are adopted, these relationships must be populated with numerical parameters. Typically, this is a two-stage process, each of which can influence the model's results. First, a benchmark data set is chosen as a basis for the model. This is typically a 'snapshot' of the economy in a given year, and represents all transactions that are to be modeled. Choice of this benchmark year anchors the functional relationships at the benchmark data points. It is generally assumed in construction of the model that in this benchmark data set all markets are in a state of equilibrium. In reality, this is unlikely to be the case, as the economy is continually in a state of adjustment. Choice of benchmark data (i.e., a specific year) can influence the results of the analysis.

A second step in the calibration process requires choosing parameters that represent how flexible agents are in moving away from this benchmark equilibrium. While these

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[4] Some CGE models are estimated, rather than calibrated, and so are not subject to this critique (McKitrick, 1998; Jorgenson and Wilcoxen, 1990). This process is, however, extremely data intensive and substantially more complex than the calibration procedure that is adopted in the studies described here and in most other applied work.

[5] A flexible functional form implies that there are no *a priori* restrictions placed on elasticities of substitution between inputs. In contrast, a restrictive functional form introduces certain rigidities simply through choice of functional form. As an example, in a Cobb-Douglas function (a restrictive functional form) the elasticity of substitution between any pair of inputs is equal to unity (1).

parameters are chosen based on empirical literature where this is available, in practice empirical estimates are often not available corresponding to the particular model structure adopted, and so parameters are often judgmentally chosen. This introduces further scope for error in model results. Even where empirical estimates of key parameters are available, there is no guarantee that such parameters, which are estimated from historical data, will continue to hold in the future (Norton et al., 1998).

In addition to the issues related to calibration, in the context of modeling climate and energy policies in particular, CGE models are sometimes seen as deficient with regards to how they represent technologies and technological change. The standard representation of technology in a CGE model is in an aggregated and highly stylized manner, through the device of a production function. These postulate a smooth relationship between various inputs and outputs, and abstract from particular technological details, instead using elasticities of substitution to capture substitutability between inputs. Several problems may arise from this approach. First, although economists are generally clear on the first-best approach to tackling energy and climate externalities, political exigencies often push decision makers towards technology-based policies, like subsidies or mandates. Policies like these are difficult to simulate using production functions. Second, production functions postulate a smooth relationship between relative prices and quantities of inputs. These may fail to capture sudden jumps or non-linearities resulting from changes in relative prices, for example as a technology reaches a 'tipping point' beyond which is becomes competitive. Third, production functions are not always transparent to non-economists, making it difficult to convey model details to policy makers. Increasingly, these constraints are pushing CGE modelers to introduce discrete technologies into their models (Bohringer, 1998). However, these are typically introduced as perfect substitutes for one another, and generally their introduction is limited to the energy supply (and particularly the electricity generation) sector.

Aside from these issues, another major detriment of CGE models is their complexity. Precisely because they do capture the feedbacks associated with linkages between various markets and agents, their results can be hard to interpret. Critics of CGE models have called them 'black boxes' because it is difficult to identify the causal pathway behind a given result. Panagariya and Duttagupta (2001), quoted in Sue-Wing (2004), say:

> Unearthing the features of CGE models that drive [their results] is often a time-

> consuming exercise. This is because their sheer size, facilitated by recent advances in computer technology, makes it difficult to pinpoint the precise source of a particular result. They often remain a black box. Indeed, frequently, authors are themselves unable to explain their results intuitively and, when pressed, resort to uninformative answers...

In contrast, in a partial equilibrium model, the causes of a change in a particular variable can generally be readily identified, since the market analyzed is treated in isolation and only exogenous shocks perturb the initial market equilibrium. In this light, the strength of CGE models associated with their realistic depiction of linkages between interrelated markets is also a fundamental weakness. Special care in interpreting and communicating model results needs to be taken to remedy this potential weakness.

In the following sections, I try to uncover the 'black box' nature of applied CGE models by building a very simple two-sector, two-commodity, one-household model from economic fundamentals. This exposition will be useful for facilitating understanding of the papers that are presented later in this thesis, where explanation of the model fundamentals is greatly truncated. My writing in this section draws in part from pedagogical articles by Sue-Wing (2004), Rutherford and Paltsev (1999), Rutherford (1999, 1995), Paltsev (2004), and Bergman (1991), among others. My aim, however, is to convey the concepts that underlie CGE modeling to an audience that includes non-economists (although some comfort with algebra and calculus is required).

I begin by describing the behaviour of individual agents in the economy. I outline how behaviour by individual actors aggregates to equilibrium in the economy as a whole. I then calibrate the model to a benchmark data set. Finally, I use the illustrative model that is developed to conduct a simple policy analysis.

3.2.2 Algebra of a CGE model

This section outlines the standard economic calculus that dictates how firms choose which inputs to use in producing goods, and how consumers choose which goods to consume. Throughout this exposition, as well as in the models that follow later in this thesis, several assumptions are made about the behaviour of firms, consumers, and the markets that connect them.

First, it is assumed that both firms and consumers behave ‘rationally’ when choosing inputs. This implies that consumer preferences are both complete and transitive,[6] and that consumers maximize utility by choosing amongst goods subject to an externally imposed budget, while firms maximize profits subject to input and output prices (Mas-Colell et al., 1995). Additionally, it requires that consumers are not satiated at high levels of consumption, that successively higher levels of consumption of a particular good are associated with smaller increases in utility (convexity), and that proportional increases in income and prices have no effect on demands (homogeneity of degree zero). Second, it is assumed that markets are competitive, such that a single price prevails for each distinct commodity, and such that both consumers and producers treat that price as fixed (they are price takers). Third, it is assumed that firms operate with constant returns to scale, such that doubling the output of a sector implies a doubling of all factor inputs.

In the following sections, the process for developing, calibrating, and solving a CGE model is described through the use of an illustrative CGE model. The model is deliberately simple and consists of just two representative firms and one representative consumer (or household). As will be described in the following sections, one firm produces an energy commodity while the other produces non-energy commodities. The simple model developed here can therefore be used for a stylized analysis of energy policies. Although the model developed here is not general, as in many other introductory descriptions to CGE modeling, the concrete example chosen here helps to facilitate understanding of this type of model, especially by minimizing the amount of notation required.

Firms

In the model, firms exist to turn inputs into outputs that consumers would like to consume. Although in the real world, firms combine an arbitrary number of primary factors of production with an arbitrary number of intermediate inputs to produce one or more final consumption goods, in this model for simplicity I assume that the only inputs used by the firm are primary factors and that only one output is produced by each firm (this is also a conventional assumption in analytical general equilibrium models). Specifically, I assume

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[6] In the context of consumer utility, an agent with a ‘complete’ preference ordering has preferences over every possible bundle of goods. Transitive preferences imply that if an agent prefers A to B and B to C, then the agent also prefers A to C.

that firms use capital and labour to produce output.

I assume that the relationship between the output of a firm and the quantity of inputs used is given by a Cobb-Douglas function:

$$X = A_X K_X^{\alpha_X} L_X^{1-\alpha_X} \tag{3.1}$$

where X is the activity level (level of output) of the 'representative' firm X, K_X is the amount of capital used by the firm, L_X is the amount of labour used, and A_X and α_X are parameters. I assume that there are two firms in the economy, each producing distinct commodities, so that the other representative firm, with similar notation, has output given by:

$$Y = A_Y K_Y^{\alpha_Y} L_Y^{1-\alpha_Y} \tag{3.2}$$

Each firm is assumed to choose the combination of inputs and outputs that maximizes its profits. Further, each representative firm is designed to represent multiple small firms, none of which is able to influence the prices of inputs or outputs. Each representative firm is therefore assumed to be a price taker. Given these assumptions, it is possible to determine the quantity of inputs that will be demanded by each firm, given prices of those inputs. In particular, I begin by writing the profit maximization problem of firm X as (and similarly for Y):[7]

$$\max_{K_X, L_X} \underbrace{p_X X}_{revenue} - \underbrace{(wL_X + rK_X)}_{costs} \tag{3.3}$$

where p_X is the price at which the firm is able to sell its output, w is the wage rate paid to the firm's workers, and r is the rental rate that the firm must pay to use capital. By substituting (3.1) into this equation, I eliminate the variable X and arrive at an equation which can be solved with standard maximization techniques:[8]

$$\max_{K_X, L_X} p_X A_X K_X^{\alpha_X} L_X^{1-\alpha_X} - (wL_X + rK_X) \tag{3.4}$$

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[7] This notation implies that the firm chooses L_X and K_X in order to maximize the function to the right.

[8] For more complicated expressions, it is standard to work with calculus of constrained maximization. I avoid that technique here in order to keep the presentation more straightforward.

In particular, a maximum point in (3.4) implies that the first derivative will be equal to zero.[9] Taking the first derivative with respect to each of the choice variables and setting the resulting expression equal to zero yields the following expressions:

$$\frac{\alpha_X p_X A_X K_X^{\alpha_X} L_X^{1-\alpha_X}}{K_X} = r$$
$$\frac{(1-\alpha_X) p_X A_X K_X^{\alpha_X} L_X^{1-\alpha_X}}{L_X} = w$$

By dividing one of these expressions through by the other I arrive at a single *first-order condition* (so-called because it originates from the first-derivatives of the objective function):

$$\frac{\alpha_X L_X}{(1-\alpha_X) K_X} = \frac{r}{w} \tag{3.5}$$

which states that the marginal rate of technical substitution between labour and capital (the term on the left hand side) is equal to the ratio of the prices of the inputs. If this condition did not hold, the firm could reduce unit costs by choosing a different combination of inputs. By substituting the first-order condition back into (3.1), it is possible to derive expressions for the factor demands of the firm:

$$K_X = \frac{X}{A\left(\frac{r(1-\alpha)}{w\alpha}\right)^{1-\alpha}} \tag{3.6}$$

and

$$L_X = \frac{X}{A\left(\frac{w\alpha}{r(1-\alpha)}\right)^{\alpha}} \tag{3.7}$$

Similar equations can be derived for firm Y.

Household

The model of the household begins with the assumption of a household utility function which expresses household preferences for each of the two goods that are produced by

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[9] A maximum point also implies that the second derivative will be negative.

firms. Utility of the household as a function of each of these two goods is assumed to follow a constant elasticity of substitution functional form:

$$U = \left(\gamma X^{\beta} + (1-\gamma) Y^{\beta}\right)^{\frac{1}{\beta}} \tag{3.8}$$

where γ is known as a ‘distribution’ parameter, and where $\sigma = \frac{1}{1-\beta}$ is the elasticity of substitution between X and Y in consumption.[10] The household is assumed to make choices over the two goods in a way that maximizes utility, given the available budget, M. The budget can be spent on either of the two goods, such that exhaustion of the budget is given by the condition:

$$p_X X + p_Y Y = M \tag{3.9}$$

This equation can be solved for Y and substituted into (3.8) to give the problem facing the household:[11]

$$\max_{X} \left[\gamma X^{\beta} + (1-\gamma)\left(\frac{M - p_X X}{p_Y}\right)^{\beta}\right]^{\frac{1}{\beta}} \tag{3.10}$$

Taking the derivative and setting it equal to zero gives, after some manipulation:

$$\frac{\gamma Y^{1/\sigma}}{(1-\gamma) X^{1/\sigma}} = \frac{p_X}{p_Y} \tag{3.11}$$

which is the first-order condition associated with utility maximization by the household. As with the producer first-order condition, this one states that the marginal rate of substitution between goods X and Y in the household utility function must be equal to the ratio of prices between the two goods. If this is not the case, the household could allocate its budget differently to increase utility. Substituting (3.11) into (3.9) gives the household (Marshallian, or uncompensated) demand functions for the two goods:

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[10] The elasticity of substitution measures the curvature of the utility function, or the rate at which relative demands change as relative prices change.

[11] As was the case when producer first-order conditions were derived, constrained maximization is typically used, especially for more complicated utility functions and budgets. Here I use substitution and unconstrained maximization instead to keep the exposition more straightforward.

$$X = \frac{M}{p_X + p_Y \left[\frac{p_Y \gamma}{p_X (1-\gamma)}\right]^{\frac{1}{\sigma-1}}} \tag{3.12}$$

and

$$Y = \frac{M}{p_Y + p_X \left[\frac{p_X (1-\gamma)}{p_Y \gamma}\right]^{\frac{1}{\sigma-1}}} \tag{3.13}$$

3.2.3 Putting it together

A full model of the economy is derived by putting together the equations above in a way that captures the concept of equilibrium in the economy. Specifically, the three sets of conditions equilibrium conditions identified in the introduction must be satisfied for the economy as a whole to be considered in equilibrium. First, in each market, the quantity supplied must equal the quantity demanded.[12]

There are four markets that must reach equilibrium for the economy as a whole to be considered in equilibrium: the market for good X, for good Y, as well as the markets for capital and for labour.

The market for good X is characterized on the demand side by (3.12) and on the supply side by (3.1). Likewise, the market for good Y is characterized by demand and supply functions (3.13) and (3.2) respectively.

I assume that the supply of labour is fixed at $\bar{L}$. Market clearance in the labour market implies that $\bar{L} = L_X + L_Y$, where L_X and L_Y are given by (3.7) (plus a similar equation for firm Y). Similarly, I assume that the supply of capital is fixed at $\bar{K}$. Market clearance in the capital market implies that $\bar{K} = K_X + K_Y$, where K_X and K_Y are given by (3.6) (plus a similar equation for firm Y).

The second condition that must hold in equilibrium (assuming perfect competition) is that no sector can make positive profits. If a sector were making positive profits, other firms

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[12] Formally, the quantity supplied can exceed the quantity demanded, provided the price of the commodity is zero. Conversely, if supply and demand are equal at equilibrium, the price for the commodity will be positive. Because of this relationship between prices and demand/supply, price is termed a complementary variable to the market clearance condition. However, while complementarity is an important feature of the solution of applied general equilibrium models, I do not deal with it further in this exposition.

would enter the sector, increasing output and driving the price down and profits to zero.[13]

There are two sectors that must satisfy the zero-profit condition in the simple model that is described here: the X sector and the Y sector. Profits are given by revenues minus costs. Non-positive profits means that costs must be at least as great as revenues. For each sector, costs are given by the product of price and quantity for both capital (3.6) and labour (3.7), while revenue is given by the product of price and quantity of output.

Finally, the third condition that must hold in equilibrium is that the consumer's budget must be exhausted, so that all income received by the consumer is spent on acquiring goods. The household budget M is derived from the household's endowments of capital and labour. The budget is therefore given by:

$$M = r\bar{K} + w\bar{L} \tag{3.14}$$

Two particular features of the equilibrium are worth noting. First, the system of equations described above is linearly homogenous in prices. As a result, any absolute level of prices is possible; only relative prices matter. A general practice is to fix the price of one of the commodities at the benchmark level (i.e., set it equal to 1), and simulate the model to observe how other prices change relative to this numeraire. However, any of the variables can be taken as fixed; for example, consumer income could be held constant. Second, a related feature of the general equilibrium structure adopted here is that if all but one of the markets that are represented are in equilibrium, then (provided the model is specified correctly) the last market is also guaranteed to be in equilibrium (this is known as Walras' Law). As a result, it is possible to drop one of the model equations when finding a solution. In what follows, I take the price of the non-energy commodity (p_X) to be the numeraire, and drop the corresponding equation from the model. I use a hat ($\hat{\cdot}$) over the price of the non-energy commodity to denote that it is held fixed at unity.

The full listing of equations is given in the box below. The full model consists of 6 equations in 6 unknowns.[14] The following sections detail the process for calibrating and

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[13] As with the market clearance condition, the zero-profit condition is associated with a complementary variable. Here the complementary variable is the activity level of the sector. If profits are less than zero, then the activity level of the sector must equal zero. Conversely, if profits are exactly equal to zero, then the activity level of the sector can be positive.

[14] The complementary variable associated with each equation is listed in parentheses.

solving the model.

Market clearance for labour (w)	$\bar{L} \geq \frac{X}{A_X\left(\frac{w\alpha_X}{r(1-\alpha_X)}\right)^{\alpha_X}} + \frac{Y}{A_Y\left(\frac{w\alpha_Y}{r(1-\alpha_Y)}\right)^{\alpha_Y}}$
Market clearance for capital (r)	$\bar{K} \geq \frac{X}{A_X\left(\frac{r(1-\alpha_X)}{w\alpha_X}\right)^{1-\alpha_X}} + \frac{Y}{A_Y\left(\frac{r(1-\alpha_Y)}{w\alpha_Y}\right)^{1-\alpha_Y}}$
Market clearance for Y (p_Y)	$Y \geq \frac{M}{p_Y+\hat{p}_X\left[\frac{p_Y\gamma}{\hat{p}_X(1-\gamma)}\right]^{\frac{1}{\sigma-1}}}$
Zero profit for X (X)	$\frac{w}{A_X\left(\frac{w\alpha_X}{r(1-\alpha_X)}\right)^{\alpha_X}} + \frac{r}{A_X\left(\frac{r(1-\alpha_X)}{w\alpha_X}\right)^{1-\alpha_X}} \geq \hat{p}_X$
Zero profit for Y (Y)	$\frac{w}{A_Y\left(\frac{w\alpha_Y}{r(1-\alpha_Y)}\right)^{\alpha_Y}} + \frac{r}{A_Y\left(\frac{r(1-\alpha_Y)}{w\alpha_Y}\right)^{1-\alpha_Y}} \geq p_Y$
Income for consumer (M)	$M = r\bar{K} + w\bar{L}$

The unknowns are X, Y, p_Y, w, r, M.

3.2.4 Calibrating a CGE model

The equations describing the behaviour of the various actors in the economy in the previous sections need to be parameterized before they can be used for applied policy analysis. Parameterization of the model is typically done with respect to a benchmark data set, which is assumed to represent the economy at equilibrium. A Social Accounting Matrix (SAM) provides a convenient way to depict the data that underlies a CGE model. Table 3.1 shows a SAM that corresponds to the level of disaggregation in the model derived above. The values are representative of British Columbia in 2004, where Y represents the energy sector, X represents all other sectors, and H is all final demands.[15]

Entries in columns of the SAM represent payments from the column account to the row account, while entries in the rows of the SAM represent receipts to the row account from the column account. The first row of the SAM shows that the household consumed \$135.67

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[15] Table 3.1 is derived from Statistics Canada Input-Output-Final demand tables as follows: the energy sector includes the Mining and Utilities sectors; energy goods include mineral fuels, electricity, and refined petroleum products; the household includes all final demands, including consumption, investment, government, and net exports; and benchmark taxes and subsidies are suppressed. As a result, the SAM is extremely simplified compared to a more detailed version.

	X	Y	H
X	-	-	135.67
Y	-	-	10.05
K	37.85	8.16	-
L	97.82	1.89	-

Table 3.1: Benchmark Social Accounting Matrix for simple CGE model. The values correspond to British Columbia in 2004, where Y is the energy producing sector, and X is the rest of the economy. All values in billions of \$2004.

billion dollars of good X and the second row shows that it consumed \$10.05 billion dollars of good Y in the benchmark year. The third row shows consumption of the capital good; \$37.85 billion were consumed in the X sector, and \$8.16 were consumed in the Y sector. The final row shows consumption of labour; the X sector consumed \$97.82 billion dollars worth of labour and the Y sector consumed \$1.89 billion dollars.

The SAM confirms the accounting principles that were identified earlier that indicate equilibrium in an economy. First, the demand for each commodity equals its supply: for example, \$135.67 billion units of good X were produced, and the same amount were consumed. Second, each sector makes no profits in equilibrium: for example, sector Y generated \$10.05 billion dollars in revenue and also spent the same amount of acquiring capital and labour. Finally, the household budget balances: income from capital and labour equals \$145.72 billion, which also equals total expenditures.

Entries in the Social Accounting Matrix are values - prices multiplied by quantities. Calibration of the CGE model involves choosing prices for each of the goods, so that quantities can be separately identified. In a simple model like the one here (without any taxes), all of the prices can be arbitrarily set to equal one (1) in the benchmark data set. Choosing the benchmark price makes no difference to the model solution. Setting the price equal to one implies that the entries in the SAM correspond to quantities as well as to values, so that, for example, the consumer consumed 135.67 units of commodity X at a price of \$1/unit.

Given benchmark quantities and prices, it is possible to solve for the missing parameters in the equations above. First order conditions for firm profit maximization (3.5) can be used to solve for the α parameters. For example, in sector X at the benchmark equilibrium:

$$\frac{97.82\alpha_X}{37.85(1-\alpha_X)} = 1 \tag{3.15}$$

so $\alpha_X = 0.279$. Using this value in (3.1) yields $A_X = 1.808$. Similar calculations for firm Y yield $\alpha_Y = 0.812$ and $A_Y = 1.622$.

For the household, an elasticity of substitution must be specified.[16] Typically, this is chosen to correspond to values identified in the literature; I choose a value of $\sigma = 0.5$ here, which implies that $\beta = -1$. Using the SAM values as well as this elasticity of substitution in (3.11) gives $\gamma = 0.9945$. Finally, $\bar{L} = 99.71$ and $\bar{K} = 46.01$ are simply the benchmark total labour and capital supply.

The full equations governing the behaviour of the economy are updated to reflect this parameterization in the box below.

Market clearance for labour (w)	$99.71 \geq \frac{X}{1.808\left(\frac{0.279w}{0.721r}\right)^{0.279}} + \frac{Y}{1.622\left(\frac{0.812w}{0.188r}\right)^{0.812}}$
Market clearance for capital (r)	$46.01 \geq \frac{X}{1.808\left(\frac{0.721r}{0.279w}\right)^{0.721}} + \frac{Y}{1.622\left(\frac{0.188r}{0.812w}\right)^{0.188}}$
Market clearance for Y (p_Y)	$Y \geq \frac{M}{p_Y+\hat{p}_X\left[\frac{0.9945p_Y}{0.0055\hat{p}_X}\right]^{0.5}}$
Zero profit for X (X)	$\frac{w}{1.808\left(\frac{0.279w}{0.721r}\right)^{0.279}} + \frac{r}{1.808\left(\frac{0.721r}{0.279w}\right)^{0.721}} \geq \hat{p}_X$
Zero profit for Y (Y)	$\frac{w}{1.622\left(\frac{0.812w}{0.188r}\right)^{0.812}} + \frac{r}{1.622\left(\frac{0.188r}{0.812w}\right)^{0.188}} \geq p_Y$
Income for consumer (M)	$M = 46.01r + 99.71w$

3.2.5 Solving a CGE model

Although for the simple model listed above, an analytic solution can be derived (see, for example Jones (1965) or Harberger (1962)), for more complex models a numerical solution is necessary. The numerical solution proceeds as follows. First, starting values for each of the variables are chosen. Second, at these points, excess demands are determined for each market. There are four markets (for X, Y, L, and K), and excess demands are given by

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[16] The elasticity of substitution for firm technology was implicitly specified as equal to one (1) through the choice of Cobb-Douglas functional forms.

demand minus supply in each of these markets. The excess demand function for good Y is, for example:

$$\Delta_{p_Y} = \frac{M}{p_Y + \hat{p}_X \left[\frac{0.9945 p_Y}{0.0055 \hat{p}_X}\right]^{0.5}} - Y \tag{3.16}$$

Additionally, excess profit functions are specified. There are two firms, each of which is associated with an excess profit function. Excess profits per unit are defined by the surplus of unit revenues over unit costs, as follows (for firm X):

$$\Delta_X = \hat{p}_X - \frac{w}{1.808\left(\frac{0.279w}{0.721r}\right)^{0.279}} - \frac{r}{1.808\left(\frac{0.721r}{0.279w}\right)^{0.721}} \tag{3.17}$$

Finally, excess consumer income is given by the difference between returns to endowments and expenditures:

$$\Delta_M = 99.71w + 46.01r - M \tag{3.18}$$

In equilibrium, there are no excess demands for goods, there are no excess profits, and no excess consumer income. The solution of the general equilibrium model therefore involves joint minimization of (3.16), (3.17), and (3.18). I denote the full set of the excess demand, profit, and income equations by $\boldsymbol{\Delta}$. The minimization problem can then be stated as one of choosing prices ($\boldsymbol{p} = [p_Y, w, r]$), activity levels ($\boldsymbol{q} = [X, Y]$), and income ($M$) such that $\boldsymbol{\Delta}(\boldsymbol{p}, \boldsymbol{q}, M) = \mathbf{0}$.

Commercial solvers are available to solve this problem. These exploit the complementarity that exists between prices and excess demands, and between activity levels and excess profits, and therefore allow for boundary solutions. For example, complementarity between prices and excess demands implies that excess demands should equal zero for positive prices, but that excess demands can be negative for zero prices. The appropriate solver is therefore one that solves a non-linear complementarity problem (NCP). PATH is the leading such solver, and is used for solution to problems throughout this thesis (Dirkse and Ferris, 1995).

PATH and other NCP solvers are based on Newtonian optimization. Figure 3.2 illustrates this procedure to solving for the root of a single variable equation (as shown in the figure, the equation is $y = (x-50)^2$). First, an arbitrary starting point is chosen; here I choose $x = 80$. At this point, the function is evaluated, this is point A in the figure. Second, the numerical derivative of the function (its slope) is evaluated at this point. This is denoted by $f'(x)$ and is shown by the dashed green line connecting points A and B. Then, this value is used to 'step' towards the root of the function by walking a distance $\frac{f(x)}{f'(x)}$ along the horizontal axis: this brings the new estimate of the root of the equation to point B in the figure. This process is updated by taking the numerical derivative at point C, and again walking along the horizontal axis by an amount $\frac{f(x)}{f'(x)}$: this time the distance is given by the dashed green line from C to D. Formally, the algorithm is given by $x_i = x_{i-1} + \frac{f(x_{i-1})}{f'(x_{i-1})}$ where the i index successive iterations. The algorithm is cycled until convergence.

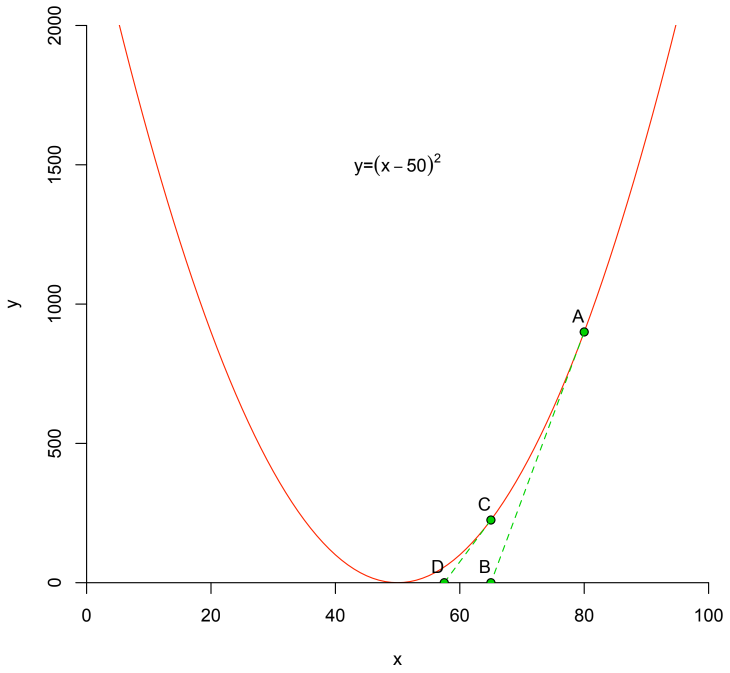

Figure 3.2: Single variable Newton optimization

For multivariate problems like the one presented here, a similar calculus applies. However, rather than a derivative, the multivariate equivalent - the Jacobian - is used. Denoting $\boldsymbol{z} = [\boldsymbol{p}, \boldsymbol{q}, M]$, the Jacobian is therefore written as:

$$\boldsymbol{J} = \frac{\partial \boldsymbol{\Delta}}{\partial \boldsymbol{z}} = \begin{bmatrix} \frac{\partial \Delta_{p_X}}{\partial p_X} & \frac{\partial \Delta_{p_Y}}{\partial p_X} & \frac{\partial \Delta_w}{\partial p_X} & \cdots \\ \frac{\partial \Delta_{p_X}}{\partial p_Y} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial \Delta_M}{\partial p_Y} & \cdots & \cdots & \cdots \end{bmatrix} \tag{3.19}$$

The Newton optimization algorithm proceeds in multivariate form via the updating procedure:

$$\boldsymbol{z}_i = \boldsymbol{z}_{i-1} + \boldsymbol{J}^{-1}\boldsymbol{\Delta}(\boldsymbol{z}_{i-1}) \tag{3.20}$$

where $\boldsymbol{J}^{-1}$ is the Jacobian inverse. As in the single variable problem, the multivariate problem continues stepping along the objective function until the error between successive iterations falls below a specified threshold.

3.2.6 A sample policy analysis

To illustrate the solution and interpretation of a CGE model, I use the simple model developed above to conduct a policy analysis. The policy I apply is a tax on the consumption of Y, which is the energy good. The imposition of the tax drives a wedge between the price that the consumer pays for Y and the price that the producer receives. As a result, the equations above must be manipulated slightly to account for the tax. First, I assume that the producer price for Y is p_Y, which means that the consumer price is $p_Y(1+\tau_Y)$, where τ_Y is the rate of the tax. The consumer price is used in determining consumer demand for Y. Second, I assume that the revenues raised from implementing the tax are collected by the government (which is not explicitly designated in the model) and rebated in lump sum to the consumer. As a result, the consumer income function must be updated to include this revenue, which amounts to $p_Y Y \tau_Y$. The updated set of equations is listed in the box below.

Market clearance for labour (w)	$99.71 \geq \frac{X}{1.808\left(\frac{0.279w}{0.721r}\right)^{0.279}} + \frac{Y}{1.622\left(\frac{0.812w}{0.188r}\right)^{0.812}}$
Market clearance for capital (r)	$46.01 \geq \frac{X}{1.808\left(\frac{0.721r}{0.279w}\right)^{0.721}} + \frac{Y}{1.622\left(\frac{0.188r}{0.812w}\right)^{0.188}}$
Market clearance for Y (p_Y)	$Y \geq \frac{M}{p_Y(1+\tau_Y)+\hat{p}_X\left[\frac{0.9945\hat{p}_Y(1+\tau_Y)}{0.0055p_X}\right]^{0.5}}$
Zero profit for X (X)	$\frac{w}{1.808\left(\frac{0.279w}{0.721r}\right)^{0.279}} + \frac{r}{1.808\left(\frac{0.721r}{0.279w}\right)^{0.721}} \geq \hat{p}_X$
Zero profit for Y (Y)	$\frac{w}{1.622\left(\frac{0.812w}{0.188r}\right)^{0.812}} + \frac{r}{1.622\left(\frac{0.188r}{0.812w}\right)^{0.188}} \geq p_Y$
Income for consumer (M)	$M = 46.01r + 99.71w + \tau_Y p_Y Y$

GAMS code corresponding to the model is included in the appendix to this chapter. The code generally mimics the equations listed below exactly, and so should be easy to interpret. When the model is declared (the line starting with MODEL), complementary variables corresponding to each equation are listed following the period.

The model is used to illustrate the impact of a tax on the consumption of commodity Y (the energy commodity). Results from three different tax rates, as well as a tax rate of zero, are shown in Table 3.2. As expected, imposition of the tax decreases the consumption (and therefore also the production) of good Y, from 10.06 units when there is no tax to 8.3 units with a 25 percent tax. Further increases in the tax result in less than proportional reductions in consumption of Y, since the marginal utility of Y increases at lower levels of consumption.

Table 3.2: Simple CGE model results

	X	Y	W/R	Welfare%	M
0%	135.70	10.06	1.00	0.00	145.76
25%	137.45	8.29	1.03	-0.14	150.21
50%	138.66	7.05	1.06	-0.44	153.34
100%	140.22	5.43	1.09	-1.19	157.47

The most interesting results, however, are those related to general equilibrium. Reductions in the consumption of Y resulting from the tax are partly offset by increases in the consumption of X, whose relative price remains lower. The welfare loss associated with a 40 percent reduction in Y (the energy commodity) is about 1.2 percent.[17] Despite the extremely simple model structure that is adopted here, this is reasonably close to estimates from other models that estimate the cost of significant (40 percent) reductions in carbon emissions, which use much more detail (see 1.2. Finally, Table 3.2 shows changes in the ratio of the wage rate to the return on capital projected by the model. As the level of the tax increases, the wage rate increases relative to the return on capital. As Table 3.1 shows, the Y sector is capital intensive relative to the X sector, so increases in the tax on Y, which reduce production of Y and therefore reduce demand for capital, tend to depress the return on capital.[18] The relative return on factors of production is important in determining the incidence of the tax. Assuming similar consumption patterns, this finding suggests that owners of capital are likely to be impacted more severely than workers as a result of a tax on energy consumption. This is explored in more detail in one of the papers included in the thesis.

3.2.7 Summary

This chapter aimed to convey a general appreciation for the strengths and weaknesses, as well as the assumptions inherent in, computable general equilibrium models. As well, the chapter outlined the process for developing a CGE model, starting from specification of the general form of the economy, through derivation of functional relationships depicting behaviour of actors in the economy, to calibration and numerical solution. More elaborate versions of this type of model are used throughout this thesis to draw conclusions relating to climate change policies in Canada.

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[17] Note that here, as well as in the papers that follow throughout the thesis, I do not attribute a welfare value to environmental improvements. Implicitly, the welfare value of these improvements would need to be at least as high as the economic welfare cost for a policy maker to implement the policy described.

[18] Another key variable affecting the relative rates of return on factors of production in the presence of a tax is the relative substitutability of factors in production as well as of commodities in demand (Fullerton and Heutel, 2007). In this model, however, all substitution elasticities in production are assumed equal to one.

3.2.8 Appendix: GAMS code for simple CGE model

```
POSITIVE VARIABLES
         W       wage rate,
         R       capital rental rate,
         PX      price of good X,
         PY      price of good Y,
         X       activity level of X,
         Y       activity level of Y,
         M       consumer income ;

EQUATIONS
         mkt_K   capital market clearance,
         mkt_L   labour market clearance,
         mkt_X   X market clearance,
         mkt_Y   Y market clearance,
         zp_X    zero-profit in X,
         zp_Y    zero-profit in Y,
         bb      consumer budget balance ;

SCALAR
         tau_Y   tax on good Y / 0 / ;

mkt_L..  99.71 =g= X/(1.808*(0.279*W/(0.721*R))**0.279) + Y/(1.622*(0.812*W/(0.188*R))**0.812) ;
mkt_K..  46.01 =g= X/(1.808*(0.721*R/(0.279*W))**0.721) + Y/(1.622*(0.188*R/(0.812*W))**0.188) ;
mkt_Y..  Y =g= M / (PY * (1 + tau_Y) + PX * (0.9945 * PY (1 + tau_Y) / (0.0055*PX))**0.5) ;
zp_X..   W / (1.808*(0.279*W/(0.721*R))**0.279) + R / (1.808*(0.721*R/(0.279*W))**0.721) =g= PX ;
zp_Y..   W / (1.622*(0.812*W/(0.188*R))**0.812) + R / (1.622*(0.188*R/(0.812*W))**0.188) =g= PY ;
bb..     M =e= 46.01*R + 99.71*W + tau_Y * PY * Y ;

MODEL    SIMPLE / mkt_L.W, mkt_K.R, mkt_Y.PY, zp_X.X, zp_Y.Y, bb.M / ;
X.L = 135.67; Y.L = 10.05; PX.FX = 1; PY.L = 1; W.L = 1; R.L = 1; M.L = 145.72;

SOLVE    SIMPLE USING MCP ;
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Chapter 4

Intensity-based climate change policies in Canada*

4.1 Abstract

Both the current and previous Canadian government proposals to reduce greenhouse gas emissions from large industries have proposed using a tradable emissions performance standard approach, where the intensity of emissions is regulated, rather than the absolute level. Unlike an absolute cap and trade system, an emissions performance standard does not guarantee a certain overall level of emission reductions, a fact that has lead to significant criticism. However, because of the dynamics of performance standards, they may reduce concerns over reductions in international competitiveness in cases where a country has climate policies that are more aggressive than some of its trade partners. Likewise, a performance standard may mesh more efficiently with existing taxes, and therefore cause less overall economic impact than an absolute cap and trade system. This paper considers the theoretical arguments for and against such a performance standard system and evaluates it in comparison to a cap and trade system using a dynamic general equilibrium model applied to Canada.

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*This paper was published in *Canadian Public Policy*, 36(4), December 2010.

4.2 Introduction

Although command and control regulations have historically dominated environmental policy, market-based approaches are becoming increasingly prominent, including for climate policy. Several northern European countries implemented carbon taxes in the early 1990s, Europe implemented a cap and trade program covering industrial greenhouse gas (GHG) emissions in 2005, Alberta implemented a tradable emissions performance standard covering emissions from large industrial sources in 2007, several US states implemented a cap and trade program for emissions from electricity generators in 2008, and British Columbia implemented a carbon tax in 2008.

Because they send a uniform price signal, encouraging all firms and consumers to reduce emissions with a similar level of effort, but still provide significant flexibility in the choice of abatement technology, economists have long promoted the virtues of market-based approaches to reducing GHG emissions. However, all market-based approaches are not the same, and differences in design can have large implications for relative economic outcomes. Given the potential scale of the 'carbon market' - with a price of \$75/t CO_2, the value of carbon permits would be equivalent to almost 5 percent of gross domestic product in Canada - these design differences could be important for overall economic performance.

Carbon taxes involve government setting the level of the tax and collecting revenue from its application, and leave the level of emissions to be determined by the responses of firms and consumers to the tax. In contrast, cap and trade systems involve government stipulating an allowable level of emissions, and leave the market to determine where those emissions should be emitted and the price that firms and consumers pay for emitting. A variant on the cap and trade approach involves government setting an allowable intensity of emissions for firms, measured in emissions per unit of product output. Firms that achieve an emissions intensity lower than the requirement obtain permits that can be traded to other firms that fail to meet it. Like cap and trade, the permit price is set by the market, rather than by government directly. This approach is referred to as a 'tradable emission performance standard' or an 'intensity-based regulation' (Newell, 2007).

For many years, Canada's national climate policy proposals have focused on the design and implementation of an intensity-based approach to reducing industrial GHG emissions. The intended policy as of 2009 (called Turning the Corner), required an 18 percent improvement in emission intensity from 2006 levels by 2010, and a further 2 percent improvement in every year following (Government of Canada, 2008). Facilities unable to reduce emissions sufficiently to comply with the regulation would be required to purchase emission permits to cover any shortfall. These credits would be generated by other firms that achieve an emission intensity lower than stipulated by the regulation, and by both domestic and international offset providers.[1] Additionally, the federal government proposed to create a technology fund, which would sell credits to firms for a government-set price. The fixed price for these credits would serve as a price ceiling (safety valve), ensuring industry that the price of emission permits would not exceed this level.

The proposed policy attracted a large amount of criticism from academics, environmental non-government organizations, and the media. Critics noted (1) that the proposed regulatory framework would only cover half of Canadian emissions, leaving the other half to grow more or less as normal; (2) that its allowance of unlimited domestic offsets and payments to the technology fund were in effect loopholes that would allow industries to avoid reducing their own emissions; and (3) that the targets embodied in the regulatory framework would be far too weak since they required stabilizing emissions at 1990 levels by 2020, as compared to much more aggressive goals promoted in European legislation and advocated by the scientific community (Partington, 2009).

Perhaps the most resonant critique of the policy related to Canada's intention to regulate the emission intensity of large industrial emitters using a tradable emissions performance standard rather than an absolute cap and trade, since critics charge that the overall amount of emissions would still be able to grow along with economic output rather than being strictly limited as in a cap and trade system (Bramley, 2007).

However, a tradable emissions performance standard may be attractive depending on the objectives and constraints facing a given government. In particular, this approach can be desirable in cases where a government wants to give a clear GHG emissions price signal that will motivate its industry to reduce emissions, but is unwilling to require industry to pay for every unit of emissions, perhaps because it suspects that major trading partners will not impose substantial emissions costs on their own industries. In this paper, we explore this issue by assessing Canada's proposed industrial emissions performance standard under al-

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[1] An offset is an equivalent emission reduction by a non-regulated entity that is paid for by a regulated firm and would count towards its emission reduction requirement.

ternative objectives and constraints facing policy makers. We outline the theoretical aspects of tradable emissions performance standards that might make them especially attractive to the Canadian government. Following this, we highlight results from an economic model of Canada that we have developed for empirically comparing a performance standard system with a cap and trade system. Both the theoretical and empirical analyses suggest that under certain circumstances the tradable emissions performance standard could reduce the overall cost and competitiveness losses compared to a traditional cap and trade system. These potential advantages come at cost however, since this approach reduces the probability of hitting strict emissions reduction targets. Additionally, the performance standard approach is much less transparent to the public than the absolute cap and trade system.

4.3 Theoretical exposition

The following discussion is divided into three parts. First, we compare a cap and trade system to an emissions performance standard in terms of the level of certainty each policy provides in (1) reaching a given emissions target and (2) reducing emissions at a predictable cost. We conclude that while only a cap and trade system assures a given level of emissions in the future, a performance standard system is better able to reduce the chance that policy compliance costs will be higher than expected. Second, we compare the static efficiency of the two policies under different scenarios: (1) a ‘first-best’ scenario when the economy is free from any distortions and the policy covers all emissions in the economy, (2) a scenario when the climate policy only covers a single country or region and other countries neglect to implement climate policies of similar stringency, (3) a scenario where the policy only covers some sources of emissions in the region and leaves others uncovered, and (4) a scenario where there are pre-existing, distortionary taxes in the economy. We conclude that although the cap and trade system is more efficient in the first-best scenario, the tradable performance standard policy may offer some advantages in the other scenarios. Finally, we summarize the literature relevant to the impacts of alternative policy designs on firm-level incentives for technical change. Here, our conclusions are more reserved, since neither the theoretical nor the empirical evidence comes out clearly in favour of a particular policy.

4.3.1 Certainty of achieving emission reductions

A conventional cap and trade system regulates the absolute level of emissions. In such a system, the regulator chooses a desired level of emissions Z, and issues that amount of permits to emitters, who are required to hold a permit for each unit of emissions released. Cost effectiveness is achieved because emitters can trade permits with one another, which, in the absence of transaction costs, should result in the emission reduction target being reached at the lowest possible cost (Montgomery, 1972). When the target is reached, the following identity holds:

$$Z = Qe \tag{4.1}$$

where Q is the output of the regulated sectors of the economy, measured in dollars or in some physical unit, and where e is the emissions intensity of the regulated sector(s), measured in units of emissions per unit of economic or physical output. Because firms are required to hold a permit to release emissions, the regulator knows with certainty the amount of emissions that will be released in the future: it will exactly equal the amount of permits issued.

In contrast, in a performance standard, the regulator sets a level of emission intensity, e. Individual firms with an emissions intensity greater than e are required to acquire permits from firms with an emissions intensity less than e, such that the overall emissions intensity of the regulated sectors of the economy reaches e. In this case, the absolute level of emissions, Z, is not set directly by the policy, but is the product of the regulated emissions intensity, e, and the unregulated economic output, Q. In theory, if the regulator can perfectly predict the future growth rate of each sector of the economy, including any impact of the policy on economic output, it can set e in the performance standard system to produce the same overall emission reductions that would be generated by a cap and trade system.

As noted, the Canadian government's proposed industrial emissions policy specified a reduction in GHG intensity for large industrial emitters of 18 percent by 2010 from 2006 levels. A recent forecast suggests that economic growth in these sectors will average 2.3 percent annually during this period (Natural Resources Canada, 2006a). If this forecast turns out to be correct, the intensity target is equivalent to an absolute reduction of 10.2

percent from 2006 levels.[2] If the future were known with certainty, the two policies - a mandate that absolute emissions in these sectors decrease by 10.2 percent and a mandate that emissions intensity in these sectors decreases by 18 percent - would produce the same reduction in overall emissions.

However, given uncertainty of economic growth, a performance standard system results in a policy outcome where emissions in the future are uncertain. If growth turned out to be 3 percent annually, emissions reductions under the performance standard system would only be 7.7 percent, rather than 10.2 percent. Lack of certainty over future emissions has been a key source of criticism for Canada's currently proposed intensity-based policy (Bramley, 2007).

In this regard, the absolute versus intensity debate parallels the cap and trade versus carbon tax debate. A carbon tax guarantees a given future price for carbon emissions (the level of the tax), but not the resulting amount of abatement by firms, which depends on how firms react to the tax. In contrast, a cap and trade system guarantees an amount of abatement (the amount of permits issued by the regulator), but not the resulting price of emission permits. A performance standard system is similar to a tax in that the amount of emissions reductions is uncertain, but is like cap and trade in that the price of emissions permits is also uncertain (but, as discussed below, the uncertainty is both variables can be less than for a tax or cap and trade system).

Weitzman (1974) analyzed the desirability of price and quantity certainty and showed that the latter is preferred in cases where the marginal benefits of emissions abatement increase more quickly than the marginal costs. For climate change, Pizer (1998) concludes that the opposite is true: deviations from the optimal quantity of emissions reductions are likely to have a much bigger impact on the marginal cost of control than on the marginal environmental benefits of abatement. As a result, a price instrument like a carbon tax is usually considered preferable to a quantity instrument like a cap and trade system for controlling GHG emissions (Pizer, 1998). However, the presence of environmental thresholds - where marginal damages change quickly with small changes in emissions - could reverse this conclusion.

Recently, Newell and Pizer (2008) and Sue-Wing et al. (2009) have extended Weitzman's analysis to compare a cap and trade system to an emissions performance standard.

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[2] $Z = Qe = (1-0.18)(1+0.023)4 = 0.898 = 1-0.102$.

Their research suggests that, in the face of uncertainty, an intensity-based approach can maintain the abatement cost closer to the level intended by the regulator than a cap and trade system, provided emissions and economic output are strongly correlated and the variance in emissions is high relative to the variance in output.[3] When these conditions hold, uncertainty in economic output is propagated through to uncertainty in emissions (because of the strong correlation between these variables). The stringency of a cap and trade system will therefore deviate from the policy maker's intended stringency, potentially imposing higher than planned costs (if economic growth is more robust than expected) or lower than planned emission reductions (if economic growth falters). In contrast, an intensity-based regulation adjusts the emission target in response to changes in output, and thus maintains the policy stringency closer to the range originally anticipated by regulators.

For these conclusions to hold, however, there must, as stated, be a relatively strong correlation between economic output and emissions. Bruneau and Renzetti (2009) show that emission intensity in the industrial sector in Canada has only changed slightly since 1990, so that changes in economic output are likely to translate to changes in emissions. Provided that such a relationship continues to hold in the future (in the scenario where no policy is implemented), it is likely that a performance standard system in Canada would result in less permit price variability than a cap and trade system. A similar conclusion was reached by Sue-Wing et al. (2009). Although the performance standard system does not offer the perfect price certainty of a carbon tax, it offers less price uncertainty than a cap and trade system. Likewise, although the performance standard system does not offer the perfect quantity certainty of a cap and trade system, it offers more certainty over the level of emission reductions than a carbon tax. In this dimension, it shares characteristics with other mechanisms that are often considered in conjunction with cap and trade systems, which increase price certainty at the expense of quantity certainty: for example, price ceilings (safety valves) and price floors to constrain the permit price to within a desirable range.

4.3.2 Static efficiency

The design of environmental policy not only affects the certainty of achieving a given level of emissions reduction, it also directly changes the incentives faced by regulated firms.

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[3] A proof of this proposition is given in Newell and Pizer (2008) and Sue-Wing et al. (2009).

This can have important consequences for the overall efficiency of the policy and for the prices of all goods affected by the regulation.

This can be demonstrated in a simple partial equilibrium model, which considers a representative firm in a competitive market.[4] In this section, for clarity of exposition we assume that the firm is in a closed economy (with no trade to or from outside countries); in the following sections we relax this and other assumptions. Profit for the representative firm, in the absence of any emission control policy, is given by:

$$\pi = (Pq) - ((c + a(\eta))q) \tag{4.2}$$

where P is the price at which the firm sells its output, q is the quantity of output produced by the firm, c is the firm's unit cost of production, $a(\cdot)$ is the cost associated with abatement of emissions, and η is a variable that ranges from 0 to 1 that represents reduction in emission intensity achieved by the firm (as a result of a policy), where 0 signifies that no abatement is undertaken by the firm, and 1 signifies that the firm has eliminated all its emissions. The firm's overall unit cost of production is given by $c + a(\eta)$. As specified, the cost does not vary with the scale of the firm. We assume that $a(\eta)$ is increasing in η (such that $a'(\eta) > 0$) and that there is no abatement cost if there is no emission abatement (such that $a(0) = 0$). The first term on the right hand side of (4.2) is the revenue from sales of the firm's output and the second term is the cost of producing that output.

In the absence of any emissions policy, the firm will pursue no abatement ($\eta = 0$). In a competitive market, the price at which the firm sells its output will be equal to the marginal cost of production, $P = c$. Now consider what happens when the firm faces an emission tax, τ, designed to reflect the social cost of emissions. The firm must pay for any emissions it produces, so the profit function becomes:

$$\pi = (Pq) - ((c + a(\eta))q) - ((1 - \eta)e_0\tau q) \tag{4.3}$$

where e_0 is the emissions intensity of the firm in the absence of any abatement effort. The final term on the right hand side represents the firm's payments of emission tax on its residual emissions (those it did not reduce when the tax was applied). The firm chooses

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[4] Similar models are presented in Fischer (2001), Goulder et al. (1999), Helfand (1991), and Holland (2009).

η to maximize its profits. In doing so, it sets its marginal cost of abatement equal to the permit price: $\frac{a'(\eta)}{e_0} = \tau$. At equilibrium the firm's cost of production has risen to $c + a(\eta) + (1+\eta)e_0\tau$. The emission tax has increased costs in two ways: first by inducing emission abatement, which is costly, and second, by forcing firms to pay a tax for any residual emissions. Given perfect competition, the increased cost of production is translated fully through to the consumer price of the good. The increased price of the good results in reduced consumer demand, assuming a consumer demand function that is not perfectly inelastic. (Remembering that this is a closed economy, a rising cost of production in a given sector will lead to rising prices for goods that do not have perfect substitutes).

Now consider what happens when, instead of imposing a tax, the regulator uses a cap and trade system to cap emissions at a socially desirable level. We assume that permits are allocated to firms in lump sum, as opposed to in an auction (an auction would be analytically equivalent to the tax case above), and we use L to represent the number of permits that are allocated to the representative firm. We assume that L is set by the regulator to reflect historic emissions; this is known as grandfathering of emission permits.[5] In this case, the profit function for the representative firm is:

$$\pi = (Pq) - ((c + a(\eta))q) - ((1-\eta)e_0\tau q - L) \tag{4.4}$$

where we treat τ as the equilibrium permit price. The firm again chooses η to maximize profits, with the same result as above: $\frac{a'(\eta)}{e_0} = \tau$. And in a competitive market, the firm sells its output at exactly the same price as in the emission tax case above: $c + a(\eta) + (1+\eta)e_0\tau$.[6] As a result, the quantity and price of that output is exactly the same as in the emission tax scenario. Grandfathering of emission permits does not affect these variables because it does not affect the marginal price of producing output; instead it is a one-time transfer that results in a profit to the firm's shareholders relative to the tax case.[7]

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[5] Throughout the paper, we assume that grandfathered permits are allocated in perpetuity to existing firms, and that the allocation is not contingent on firm operation. This is similar to the allocation scheme in the US sulfur dioxide market (Schmalensee et al., 1998). Alternative ways for allocating permits in a cap and trade system, for example based on updating rules, would generate different incentives at the firm level.

[6] In a regulated market, like the electricity market throughout much of Canada, the firm sells output at the average cost of production rather than the marginal cost of production. In this special case, the firm would pass along lump sum profits from grandfathered permits along to consumers in the form of lower prices.

[7] Sijm et al. (2006) provide empirical evidence for this phenomenon based on lump sum allocations to

Finally, we turn to the performance standard system. We assume that the regulator sets an emission intensity target given by b, where b is the rate of reduction in emission intensity required (b=0.18 for 2010 in Canada's proposed system). Firms that fail to reduce emission sufficiently are required to purchase emission permits to make up the shortfall, while firms that reduce their emission intensity by more than the target requires create permits that can be sold to others. Profit for the representative firm is now given by:

$$\pi = (Pq) - ((c + a(\eta))q) - ((b - \eta)e_0\tau q) \tag{4.5}$$

The last term in this equation represents the firm's net purchases of emission permits from other firms. The first order condition for (4.5) suggests that the firm still sets its marginal cost of abatement to the tradable permit price: $\frac{a'(\eta)}{e_0} = \tau$. However, the firm's unit cost of production is now $c + a(\eta) + \tau e_0(b - \eta)$, which is lower than both the cap and trade system with grandfathering and the carbon tax by the amount $\tau e_0(1 - \eta)$. The performance standard system has therefore given firms the same marginal signal to reduce emission intensity as the cap and trade system, but has not resulted in marginal production costs increasing by the same magnitude.

In effect, relative to the cap and trade system with grandfathered permits or the emission tax policy, the emissions performance standard acts like a subsidy to output of $\tau e_0(1 - \eta)$ per unit of production (Newell, 2007). To be clear, the performance standard system does not result in a net subsidy to firms, just an implicit subsidy relative to the cap and trade system or the emissions tax. Cost of production under the emissions performance standard will, on average, still increase relative to the no-policy case because of abatement expenditures. An alternative way to think about the tradable emissions performance standard is that it applies a price signal to stimulate firms to reduce emissions at the margin, like a carbon tax or cap and trade system, but does not force firms to pay that price for all the units of emissions they emit.

We can compare the cap and trade system with the tradable emission performance standard by assuming that the regulator has perfect information about future output and therefore can set the emissions performance standard to match the intensity that results from the cap and trade system: $b = \eta_{ets}$ (the subscript ets refers to the cap and trade system, while the subscript tps refers to the tradable performance standard). In equilibrium in our simple

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electricity generators in the first phase of the European Union Emission Trading Scheme.

closed economy, the representative firm must comply with the standard, such that $\eta_{tps} = b$.[8] As a result, the permit price in both systems is equal, $\tau_{tps} = \tau_{ets}$. The cost of production in the cap and trade system is $c + a(\eta) + (1 - \eta)e_0\tau$, while in the emissions performance standard it is $c + a(\eta)$. Because the cost of production is lower under the performance standard, the demand and therefore the equilibrium supply of output is higher, $q_{tps} > q_{ets}$. And since the emissions intensity is the same in both systems, the total amount of emissions under the performance standard is higher than under the cap and trade system, $\eta q_{tps} > \eta q_{ets}$. Conversely, to achieve the same overall emissions reductions, the emission intensity must fall further, and the permit prices must reach higher levels, in the performance standard system compared to the cap and trade system (Helfand, 1991; Goulder et al., 1999; Fischer, 2001).

In the simple model here, where there is perfect competition, no other taxes in the economy, no trade with other regions, and where the regulation covers all emissions in the closed economy, several analysts have demonstrated that both an emission tax and a cap and trade system are economically efficient policies for reducing emissions (Baumol and Oates, 1988). The tradable performance standard, which stimulates more output and emissions than the efficient level, is therefore less efficient than these alternatives (Fischer, 2001; Holland, 2009). When these idealized conditions hold, there is no economic justification for a regulator to choose an emissions performance standard to reduce emissions.[9]

In practice, most of these conditions do not hold. The regulator may not be willing to regulate emissions from all of the economy for political or administrative reasons. Canada's government can only regulate emissions from Canadian companies, not companies situated abroad. And, so far, federal regulators in Canada have been more focused on regulating GHG emissions from heavy manufacturing and extractive industries (sometimes termed 'large final emitters') than from other sectors of the economy. Finally, the economy is already significantly distorted from the first-best case by numerous taxes, suggesting that a second-best analysis is more appropriate for evaluating alternative policies. These cases deviate from the simple model that was described above, and conclusions from that anal-

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[8] In reality, there are many firms, some of which purchase permits and some of which sell permits. In this model, we are concerned with the 'representative' firm, which is intended to represent the regulated portion of the market as a whole. Since there are no net permit purchases from outside the regulated portion of the market, the firm must exactly comply with the regulation, so $\eta_{tps} = b$.

[9] This conclusion relates to the static efficiency of the policies. In a later section of this paper, we discuss the dynamic efficiency.

ysis may not apply directly to these more complicated scenarios. Each of these cases is addressed in turn.

Unilaterally applied carbon policy

We start by considering impacts of the cap and trade system when the economy is open to trade and variation exists in the GHG regulations of different countries. In this situation, Canadian firms would be regulated by the Canadian climate change policy, but firms in other regions may be regulated by other systems, or may be unregulated altogether. Emerging economies, which are increasingly important in international trade, are unlikely to subject their firms to climate policies with the same stringency as policies in wealthy countries over the next decade.

To the extent that more aggressive emission abatement increases the cost of producing goods, persistent differences in policy stringency between countries could have important implications for the international competitiveness of firms in the regulated country (Baron and ECON-Energy, 1997; Hourcade et al., 2007). In particular, increases in production costs could lead corporations eventually to shift production of carbon-intensive goods away from more stringently regulated countries, leading to loss of employment and economic output in these sectors. Fears of this type of competitiveness impact undermine the support for abatement policy in developed countries. Such concerns have been at the forefront of national debates about Canadian climate policy.

A variety of policies have been proposed to deal with this potential problem, ranging from border tax adjustments to sectoral exemptions. However, all of these face considerable hurdles related to compatibility with trade law, efficiency, and political acceptability. As an alternative, a tradable emissions performance standard provides an implicit subsidy to output relative to a cap and trade system, and so does not increase production costs by as much as a cap and trade system. In so doing, it helps to maintain the competitiveness of firms in the regulated country relative to external competitors (Bernard et al., 2007; Holland, 2009). For a country like Canada, which depends on energy-intensive primary exports for a significant share of economic activity, the emissions performance standard might be particularly attractive for this reason. Additionally, unlike border tax adjustments, a performance standard system would be unlikely to conflict with international trade law or induce retaliatory trade actions.

Imperfect coverage of emissions

The proposed federal GHG policy as of 2009 focused emissions pricing on large industrial emitters, which represent 10 to 15 percent of Canada's economic output and about half of its emissions. The remainder of the economy would not be exposed to a carbon price under the proposed policy. Such a policy contravenes standard economic theory, which suggests that all sources of emissions should be charged the same carbon price since the environmental damage associated with carbon emissions is independent of where these emissions originate, and without a common emissions charge some low cost reductions might not be pursued.

Expanding the scope of the regulatory policy so that all emissions were covered would produce greater emissions reduction at the same cost. However, there may be political or administrative reasons that inhibit expansion of the regulatory scheme to cover all emissions in the economy. In particular, limiting the policy to large industrial emitters helps to avoid the politically problematic issue of increases in household energy prices. The history of federal climate policy proposals in Canada, which have all limited emissions pricing to large industrial emitters, suggest that such political acceptability concerns have (historically, at least) been at play in this country.[10] Similar obstacles seem to have been at play in Europe, which confined its emission trading system to large industry.

A failure of government to price emissions at the same level throughout the economy could actually cause emissions to increase in sectors with low or non-existent emissions pricing. This is because the higher production costs of firms facing emissions charges and abatement costs will be passed on to consumers, inducing substitution towards goods and services that are not facing these charges. If emissions are released during production of these products, this could counteract the original intent of the climate policy. For example, Canada's federal proposal for industrial emissions pricing includes emissions from electricity generating facilities, but not emissions from residential consumption of fuels like natural gas and home heating oil. However, these fuels are potential substitutes for electricity in space and water heating, the key household energy end-uses. Increases in the price of electricity resulting from the industrial emissions pricing policy will likely cause

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[10] Specifically, all three federal policy proposals since 2002 have proposed an emissions pricing policy limited in scope to large final emitters.

some substitution from electricity toward these fuels that increases residential emissions, counteracting some of the impact of the emissions pricing policy.

Such induced substitution is obviously undesirable from an efficiency perspective, since it distorts choices made by firms and individuals without achieving reductions in emissions (Hoel, 1996). In this case, a performance standard system, which minimizes production cost increases in covered sectors, may be less problematic than an absolute cap and trade system, since it will cause less substitution from goods produced by sectors subject to the pricing policy to goods produced by sectors not subject to it (Bernard et al., 2007). The actual difference between the two systems depends on the elasticity of substitution in consumption between products of covered and uncovered sectors, as well as the degree to which Canadian firms can pass on production cost increases to consumers (in markets, like crude oil, where the price is determined internationally rather than nationally, firms would not be able to pass along cost increases to consumers, and would instead lose market share or profitability).

Pre-existing taxes

Although most analysis of environmental policy takes place under the assumption that there are no pre-existing taxes in the economy, research suggests that conclusions from such analyses can be dramatically altered when proper account is taken of pre-existing taxes (Bovenberg and Goulder, 1997; Goulder et al., 1999).

When an emissions pricing policy is implemented in a closed economy, it will raise the price of goods, as described earlier.[11] Since consumers purchase goods and services using their income, and since the emissions pricing policy raises prices of consumer goods relative to consumer income, the policy shares some characteristics with a tax on income (Bovenberg and Mooij, 1994). Essentially, the emissions pricing policy has reduced the return to income in much the same way as an income tax reduces the return to income. Both the income tax and the emissions pricing policy can therefore be expected to distort the labour market by reducing the incentive to work relative to a world of zero income taxes.

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[11] In an open economy, the policy would also raise the price of goods, except those for which international production is a perfect substitute for domestic production (crude oil is a good example of the latter).

If the emissions pricing policy is implemented on top of other income taxes, it reduces real consumer income in the same way as an increase in the income tax rate, and so amplifies the market distortion caused by the pre-existing income tax, since the marginal deadweight loss induced by labour taxation is increasing in the tax rate. This interaction between the emissions pricing policy and pre-existing taxes raises the cost of the policy above what it would have been in the absence of pre-existing taxes (Goulder et al., 1999).

Some of this tax interaction effect can be eliminated if the environmental policy also raises revenues that are used to cut the rates of pre-existing taxes. For example, revenues from British Columbia's recently-implemented carbon tax are returned to the economy as cuts to corporate and labour income taxes (British Columbia, 2008a). By reducing income and corporate taxes from their previous levels, the emissions pricing policy can reduce economic losses from application of the carbon price.

As Goulder et al. (1999) show, the recycling of emissions pricing revenues can have important implications for the overall cost of the policy. Since different policy instruments impose different costs and distribute revenue differently, it is important to consider them in light of pre-existing taxes.

In this regard, an absolute cap and trade system and an emissions performance standard differ in two significant ways. First, a performance standard system raises no revenue that government can use to cut other taxes.[12] In contrast, a cap and trade system can be designed to raise substantial revenue for government by auctioning some or all permits to emitters, which could then be used to reduce other taxes. If, however, political constraints prevent auctioning of permits in favour of grandfathering, then the cap and trade system would not generate economic benefits from efficiency-focused revenue recycling. Second, as described above, the emissions performance standard should cause smaller price increases than the absolute cap and trade with grandfathering. As a result, the performance standard should result in a smaller interaction with pre-existing taxes than the cap and trade policy.

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[12] In practice, governments may combine the performance standard with an agreement to sell an unlimited number of permits at a given price (a 'safety valve'), which would raise some revenues for government.

4.3.3 Technical change

The previous analysis focused on static efficiency concerns when the level of technology was exogenous. However, the impact of a policy on the pace and direction of technological change can play a significant role in shaping the economic impact and effectiveness of a policy over a longer time horizon (Kneese and Schultze, 1978).

We develop a simple theoretical model to illustrate how different policy instruments affect firms' incentives to develop new technologies. Like other papers in this field, we analyze the change in firms' profits as a result of an innovation that reduces abatement costs to k times the original amount (an innovation will therefore be represented by $0 \leq k < 1$) (Milliman and Prince, 1989; Montero, 2002). Using Montero's notation, we assume that policy A provides a greater incentive to innovate than policy B if $|\partial\pi/\partial k|)^A > |\partial\pi/\partial k|^B$. In other words, if the same innovation increases profits more under policy A than policy B, policy A is more likely to stimulate more innovation. This static framework is useful for highlighting the impacts of a policy on innovation in a transparent fashion, but we warn the reader that the results may be altered in a more complex dynamic model of innovation.

We first consider a cap and trade system with grandfathered permits. Using the notation developed above, profit for the firm with the technological innovation is given by:

$$\pi = (Pq) - ((c + ka(\eta))q) - [((1-\eta)e_0 q) - L]\tau \tag{4.6}$$

By reducing abatement costs, the innovation clearly increases firm profits. Similar to above, the first order conditions are: $k\frac{a'(\eta_{ets})}{e_0} = \tau$ and $P = c + ka(\eta_{ets}) + \tau e_0(1-\eta_{ets})$. Taking the total derivative, and using the envelope theorem, we get:

$$\frac{d\pi}{dk} = -q_{ets}a(\eta_{ets}) \tag{4.7}$$

This indicates that as k gets lower as a result of innovation, profits increase proportionately to the total cost of abatement.

Now we consider the incentive to innovate under a performance standard. To keep the two instruments comparable, we again assume that the regulator maintains the emission intensity the same in the performance standard as in the cap and trade system, $\eta_{tps} = \eta_{ets}$. Profit is then given by:

$$\pi = (Pq_{tps}) - ((c + ka(\eta_{ets}))q) \tag{4.8}$$

The first order condition relating price to marginal cost is: $P = c + ka(\eta_{ets})$. As we showed above, because the marginal cost is lower, we would expect consumer demand and therefore output to be higher, $q_{tps} > q_{ets}$ (provided consumer demand is not perfectly inelastic).

The total derivative of (4.8) is:

$$\frac{d\pi}{dk} = -q_{tps}a(\eta_{ets}) \tag{4.9}$$

Since $q_{tps} > q_{ets}$, we have $|\partial\pi/\partial k|^{tps} > |\partial\pi/\partial k|^{ets}$ when the performance standard is set to mimic the emission intensity under a cap and trade system. In other words, the incentive for innovation under the performance standard will be greater than under the cap and trade system. The intuition is straightforward: because output is higher under the performance standard, the total amount of abatement is larger, and so innovations that reduce abatement costs are valued more highly.[13]

While this simple model suggests that incentives for innovation may be higher under a performance standard than under a cap and trade system, we emphasize that this conclusion is tentative. In particular, our model considers only the innovation phase and does not consider how diffusion of the technology affects firm incentives to innovate, nor how a dynamic regulator (who responds to the innovation by altering the abatement policy) may affect such incentives. These issues are dealt with by Milliman and Prince (1989). Further, it does not consider the possibility that competition in the output or permit market is imperfect, which introduces substantial complexity to the analysis (Montero, 2002). Nor does it consider the case where innovation is costly and may not be perfectly appropriated by the innovating firm. These complexities are addressed by Fischer et al. (2003). In these more complicated analyses, it is not possible to draw strong conclusions on the superiority

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[13] If, instead of matching the intensity under the performance standard to the intensity under the cap and trade scheme, the regulator chose the match the emissions under the two policies, the incentive for innovation under the performance standard would still be higher. In this case, output is again higher under the performance standard system (because of the 'dilution effect' identified by Hefland), and abatement is also greater. Since abatement is greater, innovations that reduce abatement cost are more highly valued (Bruneau and Renzetti, 2009).

of alternative policy instruments for promoting innovation. In fact, although there is fairly widespread acknowledgement of the importance of induced technical change in evaluating alternative policy instruments, the theory is still somewhat unclear on which policy designs lead to superior innovation incentives, especially as simplifying assumptions are relaxed. Additionally little empirical testing has been conducted to evaluate these alternative theories of innovation incentives.

4.4 Modeling analysis

Policy makers designing climate policy need to trade off between potentially competing objectives. A critical trade-off is between the environmental effectiveness of policies and their effect on economic output. As the previous discussion highlighted, the choice between an absolute cap and trade system and an emissions performance standard involves both of these objectives.

While the previous discussion outlined in theoretical terms some of the key distinctions between the policies, it is critical to know how these effects interact with one another, as well as the overall effects of the alternative policy approaches. To this end, this section presents an evaluation of the absolute cap and trade system and the emissions performance standard using a quantitative model of the Canadian economy. The model is a single-region dynamic computable general equilibrium model, similar to the type used for tax policy analysis (Baylor and Beausejour, 2004), and for many studies of environmental policy (McKitrick, 1997; Paltsev et al., 2007). The model contains a detailed representation of the transactions in the Canadian economy, including transactions amongst firms, between firms and consumers, and between Canada and other countries. Like most models of this type, it operates under the assumption that Canada is a small open economy, with negligible effect on world prices. Additionally, it includes a relatively detailed accounting for pre-existing taxes in the economy, as well a representation of government spending and transfers. The model is calibrated to Statistics Canada's System of National Accounts, and energy consumption data are included from Statistics Canada's Report on Energy Supply and Demand (RESD). A more detailed description of the model is included in the appendix.

Two important limitations of the model are worth mentioning explicitly. First, the model treats technology as exogenous, and so does not account for the possibility of policy-induced technological innovation, as described in the earlier discussion. This is a drawback shared with most models of this type.[14] Including endogenous technological change in the model would likely reduce our estimates of the economic impact of climate change policy. Second, the model treats population as exogenous. One way to meet an emission target would be to change immigration policy - a possibility we do not explore.

We use the model to compare an absolute cap and trade system and an emissions performance standard covering GHG emissions from Canada's large industrial emitters. For the cap and trade system, we model two variants: one where government auctions permits and uses all revenues to lower the pre-existing labour income tax (this is analytically equivalent to a carbon tax with revenue recycling), and another where government allocates permits free to firms based on their initial level of emissions (grandfathering). To account for the complicating factors described in the previous section, the model accounts for international trade between Canada and other countries (and assumes that Canada implements a climate policy unilaterally), accounts for the fact that consumers may substitute from products of sectors facing emissions pricing to products of sectors without emissions pricing, and includes a detailed accounting of pre-existing taxes in the economy.

To make the policies directly comparable, the model is run such that each of the policies reduce emissions from the large industrial emitters by the same amount. The quantity of emissions reduction is based on the Canadian government's 2008 Turning the Corner policy proposal, which specified that existing large industrial emitters would be required to reduce emission intensity by 38 percent below 2006 levels by 2020 (Government of Canada 2008). Given projected growth in output from these sectors, this works out to about a 15 to 20 percent (absolute) reduction in emissions from 2006 levels (for these sectors only). This target is used as a constraint for the large industrial emitters in the simulations that follow.[15]

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[14] Some energy-focused CGE models do model the process of technological change explicitly, but mostly these are very aggregated and not appropriate for answering the policy questions examined here (Bosetti et al., 2006).

[15] To maintain focus on comparing the tradable performance standard policy with the cap and trade policy, other details of the *Turning the Corner* proposal are not modeled. In particular, policies aimed at other sectors are not modeled, and some of the compliance mechanisms for large industrial emitters are not included. For example, while the *Turning the Corner* proposal allows large industrial emitters to meet emission obligations by purchasing technology fund credits and international and domestic offset credits, in addition to inter-firm trading and in-house reductions, the modeling described here includes only the last two compliance options.

Table 4.1 shows the model projections for the overall impact of the three policies. As suggested by the earlier theoretical analysis, the equilibrium permit price needed to reach the same level of emissions reduction under the emissions performance standard is significantly higher than under the absolute cap and trade system. This increased permit price reflects the additional distortion caused by the implicit output subsidy present in the intensity-based allocation scheme. In the model results presented here, the equilibrium permit price in the emissions performance standard is roughly double the price in the cap and trade system, suggesting that the choice of allocation method can have a dramatic impact on emission price. This is consistent with results from Fischer and Fox (2008) and Dissou (2005). Likewise, it is close to results from Dissou (2006), who evaluated a similar cap and trade system with output-based allocation of emission permits. All three policies reduce emissions from the large industrial emitters by the same amount (by design). Impacts on the non-covered sectors are similar between policies.[16] Overall, the policy allows for significant growth in emissions by 2020, since about half of the economy is not covered by a carbon policy.

The impact on overall economic output is dependent on the policy design. Table 4.1 shows that the absolute cap and trade system is projected to result in a reduction in GDP from projected levels of about 0.7 percent by 2020 if the revenues are recycled in lump sum to households, and of about 0.4 percent when the revenues are used to cut the existing labour income tax. In contrast, the emissions performance standard is projected to reduce GDP by less than 0.1 percent from projected levels by 2020. Figure 4.1 shows the transitional impacts of the policy on economic output; the impacts of the policy in 2020 are quite similar to the long-run impacts of the policy on economic output. It is useful to

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Thus, the results should not be taken as an accurate simulation of the total federal government policy, but rather as indicative of the likely effects of the emissions performance standard component of that policy relative to alternatives.

[16] There are slight differences in emissions from non-covered sectors between the policies. These differences reflect the combination of two effects: a substitution effect, which was described earlier in the paper, encourages consumers to shift consumption towards covered sectors under the performance standard relative to the cap and trade system, because prices do not rise as much under the performance standard. This reduces emissions from non-covered sectors in the performance standard. Second, an income effect is present, since under the performance standard national income is higher than under the cap and trade system, increasing consumption of all goods. This increases emissions from non-covered sectors under the performance standard.

translate these impacts into growth rate impacts, since that is usually how economic output is reported. Under the cap and trade system, the economic growth rate would be reduced by less than 0.1 percentage points over the 2010-2020 period, while under the performance standard system, the economic growth rate would be relatively unaffected.

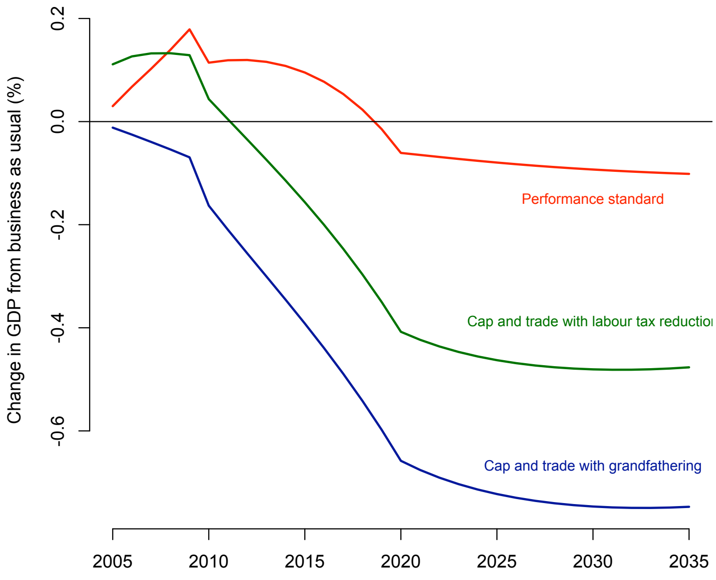

Figure 4.1: Economic growth under alternative policies

As shown in Table 4.1, the cap and trade system with grandfathered permits results in a reduction in the real wage rate, reflecting increases in the prices of consumer goods under the carbon policy. This results in a reduction in labour force participation. In this policy, allocation of permits in lump sum results in an increase in non-labour income for consumers. Since leisure is a normal good in the model, this increases the demand for leisure and so decreases labour supply. The overall reduction in labour supply is about 0.8 percent. In contrast, the other policies do not feature large increases in non-labour income for consumers, and wage rates do not drop as much, so labour force participation remains much higher than when permits are allocated through grandfathering.

Finally, Table 4.1 also shows the impact of the policy on household welfare. This measure shows the change in the lifetime income of the representative consumer that would, in the eyes of the consumer, exactly equal the negative impact of the policy (equivalent variation). The model suggests that the absolute cap and trade system is projected to reduce consumer welfare by about 0.25 percent. For a household with an after-tax income of \$60,000 (roughly the Canadian median in 2007), this works out to about \$120 annually.[17] In contrast, the emissions performance standard and the cap and trade system with labour tax recycling are projected to reduce welfare by a lower amount.

Although we do not present results here, we have conducted a wide range of sensitivity analyses on model parameters, including on Armington (trade) elasticities, on production and consumption elasticities, and on assumptions related to factor mobility. Although the results are sensitive to changes in parameter values, the ranking of policies remains invariant to changes in parameter values, and the overall economic impacts of the policy remain the same order of magnitude.

The results in Table 4.1 suggest that the emissions performance standard, by providing an implicit output subsidy to emitters, can help to mitigate some of the overall economic consequences of climate policy, under certain real-world constraints facing countries seeking to implement immediate emissions pricing policies. In addition to these overall economic impacts, Figure 4.2 shows that the policy can have important impacts on the international competitiveness of firms in regulated sectors. The figure shows the impact on output from each sector as a result of change in net exports.[18] This is a good measure of the competitiveness of a policy because it accounts for any changes in market share of a sector in both domestic and international markets (Jaffe et al., 1995). The left hand side of

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[17] In the dynamic framework adopted here, the relevant measure is lifetime income, however, we present numerical results in terms of annual income because these are more familiar. Like most models used to conduct this type of analysis, the one employed here does not consider the environmental benefits associated with reduction of greenhouse gas emissions. The welfare measure reported here therefore only considers the economic costs of abatement, not the environmental benefits of abatement.

[18] The figure does not show the total change in sector output, just the change in sector output resulting from changes in net exports. Demand for a sector's products can change for three reasons in the model: (i) because total domestic demand changes, (ii) because the sector becomes less competitive in international markets, and (iii) because domestic consumers substitute imported goods for domestically produced goods. Since (i) can be an intended result of the policy (for example, the policy is designed to reduce domestic demand for fossil fuels) the figure only shows impacts of (ii) and (iii) on sector output.

Table 4.1: Overall impact of the cap and trade and performance standard systems

	Cap and trade + granfathering	Performance standard	Cap and trade + labour tax
Real CO_2 price ($/t CO2), 2020	64	117	65
Welfare (equivalent variation)	-0.24%	-0.18%	-0.11%
Real 2020 GDP loss from changes in:			
Consumption	-0.27%	-0.11%	-0.07%
Investment	-0.35%	0.03%	-0.29%
Government purchases	-0.07%	0.01%	-0.08%
Net exports	0.03%	0.01%	-0.08%
Total	-0.66%	-0.06%	-0.41%
Change in 2020 emissions in Mt CO_2 (relative to 2006):			
LFE	170	170	170
Others	3	0	2
Total	173	170	172
After-tax wage rate, 2020	-0.82%	0.11%	-0.02%
Labour supply, 2020	-0.27%	0.11%	0.02%
Real exports, 2020	-0.03%	-1.00%	-0.12%
Real imports, 2020	-0.32%	0.15%	1.04%
Price of foreign exchange, 2020	1.01%	0.15%	1.04%

the figure shows impacts on the large industrial emitters. Under the absolute cap and trade system, international competitiveness of several of these sectors is expected to deteriorate as a result of extra costs imposed by the requirement to purchase emission permits. Under the emissions performance standard however, the price of outputs does not rise by as much, which somewhat mitigates the competitiveness impacts associated with the policy. In fact, several large industrial sectors, in particular those that have access to low-cost emission reduction opportunities and those that use a significant amount of inputs whose price falls in general equilibrium, are projected to increase in international competitiveness as a result of the emissions performance standard system.

In the figure, the oil and gas and mining sectors stand out: both of these sectors are projected to experience boosts in net exports as a result of climate policy. This somewhat counterintuitive result occurs because domestic demand for fossil fuels, which are the product of these sectors, falls significantly. This reduces the domestic price of fossil fuels, which reduces imports. Meanwhile, the international price of fuels remains stable, so domestic producers shift production from domestic markets to export markets. The combination of reductions in imports and increases in exports causes significant increases in net exports. It should be cautioned, however, that the overall level of output from these sectors drops as a result of declining domestic demand; the figure just shows changes in net exports.

At the beginning of this paper, we discussed the differences between a cap and trade system, an emission tax, and a performance standard in the presence of uncertainty about costs and benefits of emission mitigation. Here, we use the quantitative model to illustrate our arguments in the presence of a specific type of uncertainty: future growth rates.

Consider a regulator with imperfect knowledge over future economic growth rates, who chooses a policy today to regulate emissions through to 2020. The regulator can set a fixed emission tax, use a cap and trade system to cap the overall level of emissions, or use a performance standard to regulate emission intensity. If there is no uncertainty about future growth rates, the regulator can set each policy to produce the same level of emissions. However, if growth rates are different than predicted by the regulator, future emissions will depend on the specific policy instrument chosen by the regulator. Likewise, the emission price will also depend on the interaction between the policy instrument and the uncertain growth rate.

To generate results, we simulate uncertainty in future economic growth by altering the

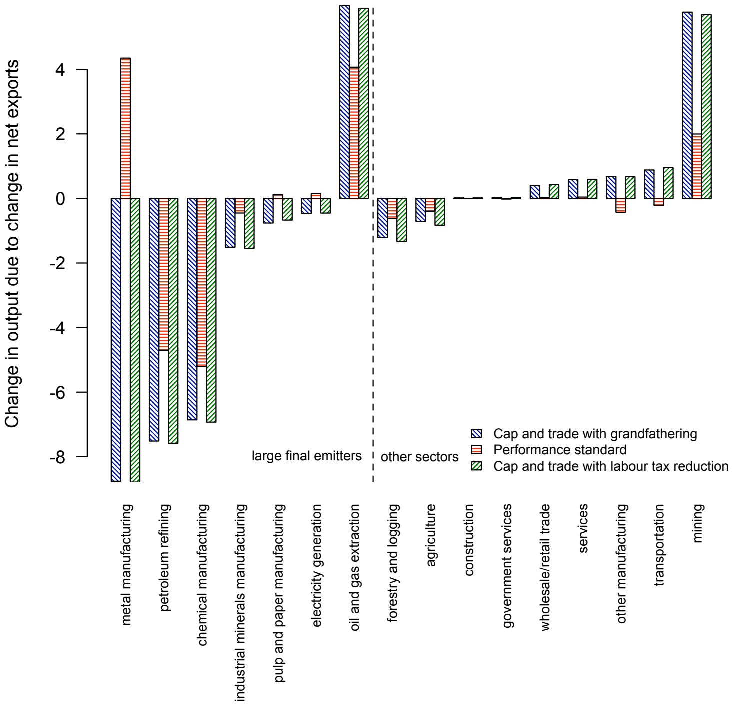

Figure 4.2: Competitiveness under alternative policies

exogenous rate of Harrod-neutral (labour augmenting) technological change in the model. In the base case, annual technological improvement is set to 1.25%, and all policies are set by the regulator to produce the same level of emissions in 2020 given this anticipated growth rate.[19] We hold all policies fixed at this level, and then test for differences in outcomes when the growth rate deviates from the forecast level; we test a HIGH and LOW case where technological change improves labor efficiency by 1.75% and 0.6% annually, respectively.

We illustrate results in Table 4.2, where the left panel shows changes in total emissions from regulated industries (large final emitters) compared to the base case, and the right panel shows changes in the emission price compared to the base case, when economic growth is either higher or lower than expected. Under the cap and trade system, the

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[19] We assume that the regulator holds each policy fixed regardless of the rate of economic growth. While this is useful for illustrative purposes, it is possible that the regulator would change the stringency of each policy in response to the growth rate.

regulator fixes the level of emissions, and so this does not change with economic growth. However, because of the fixed level of emissions, a higher growth rate means that the cap on emissions becomes more binding, and the price of emission permits increases. This is illustrated in the right panel, where a high growth rate leads to emission prices 24% higher than originally anticipated by the regulator. Likewise, a low growth rate means that the cap becomes less binding, meaning that emission prices fall relative to expectations - by 30% in the scenario examined here. In contrast, a tax fixes the emission price, so this is unchanged no matter the rate of economic growth. But with a fixed tax rate, higher growth means higher emissions. This is illustrated in the left panel, where a high growth rate leads to 5% more emissions than anticipated by the regulator and a low growth rate leads to 8% less emissions than anticipated. Under a performance standard, neither the emission price nor the level of emissions is fixed; instead the policy fixes emission intensity. Provided economic growth does not impact emission intensity or the abatement curve, we would expect no change in the stringency of the policy under economic growth. However, in the model, new plants are treated as flexible, whereas old plants are treated as fixed (they are unable to alter inputs in response to changes in relative prices). As a result, more growth means a lower emission intensity abatement curve (since flexible, new plants make up a higher proportion of the total capital stock), and thus a lower emission price needed to reach a given level of emission intensity. The table shows that the emission price is 6% lower than expected with a high growth rate. With a lower emission price as well as a higher overall growth rate, overall emissions grow by 7% - even higher than under the emission tax.[20] Likewise, if the growth rate is lower than expected, the emission price under the performance standard is higher, and the level of emissions is 10% lower than expected.

4.5 Conclusion

The choice of emissions pricing policy to reduce GHG emissions - emissions tax, cap and trade system, or tradable emissions performance standard - can affect the policy's economic impacts. This paper has explored these alternative policies first using a simple analytical approach and then using a computable general equilibrium model applied to Canada. We

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[20] In the theory section described above, we did not differentiate between "new" and "old" plants, and so reached somewhat different conclusions than in this quantitative analysis.

Table 4.2: Emissions and emission price under growth uncertainty

	Emissions (LFE only)		Emission price	
	HIGH	LOW	HIGH	LOW
Performance standard	+7%	-10%	-6%	+13%
Cap and trade			+24%	-30%
Emission tax	+5%	-8%		

find that although an emissions tax or an absolute cap and trade system is probably the optimal policy in a first-best economy, where all sources of emissions are regulated, and where there are no pre-existing tax distortions, emissions performance standards may offer some advantages in a second-best economy. In particular, because they do not raise the cost of production in key emissions-intensive sectors by as much as the other policies, emissions performance standards are likely to have less impacts on the international competitiveness of carbon-intensive industrial sectors in a world where the emission pricing policies of other countries are less aggressive or non-existent. Given Canada's trade-dependent economy, this could be an important feature of a greenhouse gas mitigation policy.

Of course, the potential economic benefits of the emissions performance standard approach are associated with trade-offs. Unlike an absolute cap and trade system, an emissions performance standard does not offer certainty over future emissions levels. Also, the emissions performance standard may be difficult to integrate with the emissions pricing policies of other countries, should most of these opt for some type of absolute cap and trade system, as appears to be occurring. While permits could (in theory) be tradable between countries with cap and trade systems and emissions performance standards, the differing incentives offered by a performance standard may mean that countries with cap and trade systems may be reluctant to allow such permit exchanges. Perhaps most importantly, the use of an emissions performance standard on its own raises no revenue for government to apply in lowering other taxes, funding technology development and deployment, or addressing equity issues imposed by adoption of climate policy. If, however, the policy included an emissions price ceiling (safety valve), this could provide some revenue, as would be the case with the proposed Canadian emissions performance standard. Finally, the performance standard system may be less transparent than the absolute cap and trade system, since it may not be readily apparent to the public whether a particular intensity requirement requires significant effort on the part of emitters, or whether it would be reached even without a policy.

4.6 Appendix

The model is a single-region dynamic general equilibrium model of the Canadian economy. A forward-looking representative household is endowed with an exogenous labour endowment that can be used to produce labour or consumed as leisure, and an initial capital stock that accumulates over time through endogenous savings and investment decisions. The household provides labour and capital services to firms, who combine these with intermediate material and energy inputs to produce commodities. Commodities can either be consumed domestically or exported to world markets under the assumption that Canada is a small open economy that does not affect world prices for commodities. A government agent is also specified, which collects all taxes in the model, and which produces an exogenously given level of government services. Important aspects of the model are described in the following sections.

4.6.1 Household

The representative household is forward-looking, and chooses consumption to maximize discounted utility:

$$\max_{c_t} \sum_{t=1}^{T} \left(\frac{1}{1+\rho} \right)^t u(c_t) \tag{4.10}$$

where T is the time horizon of the model, ρ is the rate of pure time preference, c_t is full consumption (including leisure), and $u(c_t)$ is the instantaneous utility of consumption, given by:

$$u(c_t) = \frac{c_t^{1-\theta} - 1}{1-\theta} \tag{4.11}$$

where $\sigma_t = 1/\theta$ is the elasticity of intertemporal substitution.

Instantaneous consumption is based on a nested constant elasticity of substitution function, as shown in Figure 4.3, where σ_n is the elasticity of substitution for nest n. This structure imposes an endogenous labour supply in the model, as households are able to adjust their provision of labour in response to the after-tax wage rate. The parameter σ_{cl} is chosen so that the uncompensated labour supply elasticity in the model matches the exogenously given parameter ε_{ul}. The detailed nesting of energy commodities allows for realistic response of consumer demand in response to changing relative energy prices.

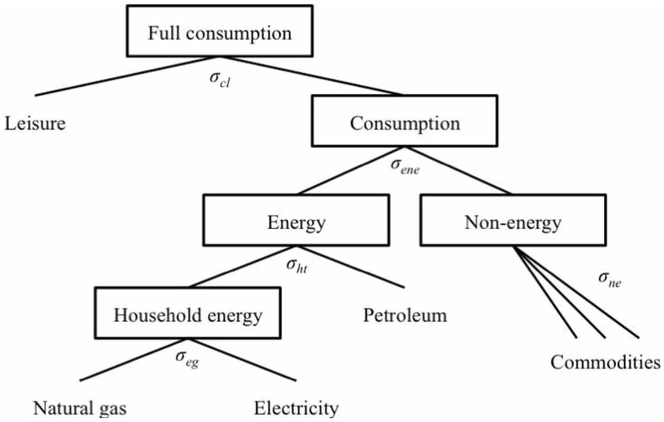

Figure 4.3: Nesting structure for household consumption

The consumer maximizes intertemporal utility such that the intertemporal budget balances:

$$\sum_{t=1}^{T}\sum_{i} p_{it} g_{it}(1+tc_{it}) = \sum_{t=1}^{T}\left(\frac{(L_t - l_t)w_t}{1+td_{lt}}\right) + TRN_t + \frac{K_0 r_0}{1+td_{k0}} - \frac{K_T r_T}{1+td_{kT}} \tag{4.12}$$

where p_{it} and g_{it} are the prices and quantities of good i in period t, tc_{it} are the taxes on final consumption, TRN_t represents lump sum transfers from government to households, L_t is the total labour endowment, l_t is the leisure consumption, w_t is the gross wage rate, td_{lt} is the direct tax on labour income, td_{kt} is the direct tax on capital income, r_t is the rental rate on capital, and K_t is the capital stock. The final two terms on the right hand side represent the value of the initial capital stock and the post-terminal capital stock, respectively.

4.6.2 Production

Production of goods in each sector j in each time period is given by a constant returns to scale, constant elasticity of substitution function, with nesting designed to represent detailed substitution possibilities between different fuel types, and between energy and value added. The nesting structure is given in Figure 4.4, where σ_m is the elasticity of substitution within nest *m* (sector subscripts have been dropped for clarity). At each level of the nest, producers choose inputs to minimize unit costs given the constant elasticity of substitution structure and the particular parameter choice for the substitution elasticity. For extractive sectors, a fixed resource input is required along with other factors of production. For these sectors, the elasticity of substitution σ_{ff} is chosen such that the own price elasticity of supply for the sector's output matches an exogenously-supplied elasticity, σ_f. The model does not address resource depletion issues, so that the fixed factor resource is available throughout the simulation period. Corresponding to the rectangular structure of Canada's input-output tables, the nesting structure allows multiple commodities to be produced by each sector. Choice of commodity production in each sector is governed by a constant elasticity of transformation function, with elasticity of transformation σ_t.

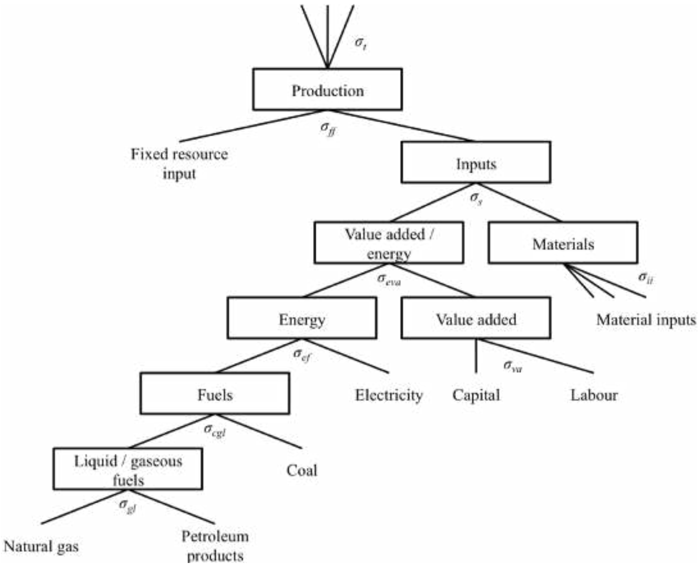

Figure 4.4: Nesting structure for firm production

Producers maximize profits, and profits for each sector are zero in equilibrium:

$$\pi_j = p_j Y_j - rK_j(1+tf_{jk}) - wH_j(1+tf_{jl}) - \sum p_{in} in_j \tag{4.13}$$

where p_j is the price of output, tf_{jk} and tf_{jl} are the factor taxes rate on factors of production, p_{in} is the price of inputs, and in_j is the quantity of inputs.

4.6.3 Government

One government agent represents all three levels of Canadian government (federal, provincial, and municipal). Government collects net tax revenue (less subsidies), including both direct and indirect taxes. Taxes included in the model are (1) a direct labour income tax and (2) a direct corporate income tax, (3) an indirect factor input tax/subsidy on producers, (4) a consumption tax on final consumption and investment, and (5) import tariffs. The rates of all indirect taxes and subsidies are calibrated to the input output data, while the rates for direct taxes are derived from separate data on direct income taxation. All taxes are assumed to remain constant throughout the simulation unless endogenously modified (as described in the text). When a carbon price is applied, government is considered the owner of emission permits (or the collector of tax receipts, in the case of a carbon tax) unless otherwise noted.

Government expenditures finance provision of an aggregate public good (health, education, defense, etc.). In all simulations, provision of the aggregate public good remains constant at reference case levels. Remaining government budget is transferred to households in lump sum unless otherwise specified. Government is subject to an intertemporal budget constraint such that all net tax revenue is balanced by expenditures and transfers.

4.6.4 Trade

To allow for cross-hauling, the model uses an Armington formulation for international trade in which domestically and internationally produced goods are treated as imperfect substitutes. In particular, each domestic consumption good i is a constant elasticity of substitution aggregate of domestic and foreign goods:

$$A_i = \left(\alpha_{hf,i} h_i^{\gamma_{hf,i}} + (1-\alpha_{hf,i} f_i^{\gamma_{hf,i}}\right)^{1/\gamma_{hf_i}} \tag{4.14}$$

Where A_i is the Armington aggregate, h_i and f_i are the quantities of domestic and foreign good, respectively, α_{hf} is a constant determined through calibration, and where $\sigma_{hf,i} = 1/(1-\gamma_{hf,i})$ is the Armington elasticity. For exports, a similar constant elasticity of transformation is applied to each domestic production industry:

$$Y_i = \left(\alpha_{dx,i} d_i^{\gamma_{dx,i}} + (1-\alpha_{dx,i} x_i^{\gamma_{dx,i}}\right)^{1/\gamma_{dx_i}} \tag{4.15}$$

where d_i and x_i are the quantities of domestically produced good for domestic and export markets, respectively, α_{dx} is a constant determined through calibration, and where $\sigma_{dx,i} = 1/(1-\gamma_{dx,i})$ is the domestic-export transformation elasticity.

Trade in commodities is mediated through the foreign exchange market, which allows Canadian currency to appreciate or depreciate relative to foreign currencies.

4.6.5 Factor markets

Population is assumed to grow at an exogenous rate, determined by exogenous federal government forecasts of population. An exogenous labour productivity growth factor is applied to the population to generate an endowment of potential labour supply. As described in the section on consumer utility, the labour supplied to production is endogenous, since consumers can choose leisure consumption as a function of the real wage rate. Labour is treated as an aggregate, is assumed to be perfectly mobile between sectors, and the labour market is assumed to be perfectly competitive.

The capital stock owned by households in the first period is determined by calibration to the benchmark data set. Thereafter, the capital stock evolves endogenously, based on savings and investment decisions, as described in the following section. The initial capital stock owned by households is assumed to be sector-specific fixed capital. Vintages of capital installed during a model run are assumed to be perfectly malleable between sectors. Canada has access to the international capital market, where it can borrow or lend at an exogenous international interest rate, subject to an intertemporal borrowing constraint.

4.6.6 Dynamics

Consumers endogenously choose how much of total output to invest in a given period. The capital stock evolves subject to these investments:

$$K_{t+1} = K_t(1-\delta) + I_t \tag{4.16}$$

where K_t is the total capital stock in time t, δ is the rate at which the capital stock depreciates, and I_t is the total investment in period t. Overall investment is a constant elasticity of substitution aggregate of investment goods:

$$I = \left(\sum_i \alpha_{Ii} A_{Ii}^{\gamma_i}\right)^{1/\gamma_i} \tag{4.17}$$

where α_{Ii} is a calibrated constant, A_{Ii} is the quantity of Armington commodity i used for investment, and where $\sigma_I = 1/(1-\gamma_I)$ is the elasticity of substitution between investment commodities.

Investment is a 'zero-profit' activity:

$$r(1+\phi)I - \sum_i p_i A_I i(1+ti_i) = 0 \tag{4.18}$$

where ϕ is the interest rate, and ti_i is the ad valorem tax on investment demand for good i.

Because the model has a finite horizon, a constraint is needed for final period investment. Following Lau et al. (2002), the following constraint is used:

$$\frac{I_T}{I_{T-1}} \geq \sum_J \frac{Y_{J,T}}{Y_{J,T-1}} \tag{4.19}$$

4.6.7 Emissions

Greenhouse gas emissions are directly proportional to combustion of fossil fuels. Emissions policy is simulated by requiring all emitters of fossil fuels to hold a permit (or pay a tax) for each unit of greenhouse gas emitted. Because of the detailed nesting structure adopted, emitters have a choice of substituting between fuel types or improving energy efficiency in order to avoid emissions. Unless otherwise noted, emission permits are initially owned by government and are distributed to emitters in lump sum. The permit market is assumed to be perfectly competitive.

4.6.8 Data and calibration

Data on the financial flows underlying the model is derived from the annual economic accounts published by Statistics Canada (tables 381-0009 and 381-0010). The economic accounts data in Canada is structured as a rectangular matrix (in which each sector can produce multiple commodities), and this structure is maintained in the model development. The economic accounts data is supplemented with additional data on direct taxation (Statistics Canada table 385-0001), energy consumption (Statistics Canada tables 128-0002 and 128-0009), and greenhouse gas emissions coefficients (Natural Resources Canada 2006).

The model includes 16 sectors and 21 commodities. The level of aggregation is chosen to balance a relatively high level of useful detail with the computational requirements imposed by a dynamic model. Table 4.3 summarizes relevant data at a sector level. Overall, the energy value share in production is 3.7 percent, but there are several sectors for which production is much more energy intense: in particular electricity generation, petroleum refining, chemical manufacturing, and the agriculture sector. The table also illustrates the open nature of the Canadian economy, where roughly 20 percent of domestic consumption is imported and 20 percent of domestic production is exported. Some sectors - especially energy-intensive sectors - have much higher trade exposure than the average.

Table 4.3: Sector characteristics, 2005. Output is measured in 2005 dollars, export share is the percent of production that is exported, import share is imports as a fraction of consumption, energy share is the value share of energy in production, and carbon share is the imputed value share of carbon in production with a carbon permit price of \$50/t CO2e.

	Output	Export share	Import share	Energy share	Carbon share
petroleum product manufacturing[a]	64,856	25.2%	14.7%	16.9%	3.9%
agriculture[b]	41,394	19.8%	17.0%	11.7%	2.4%
forestry and logging[b]	16,076	13.4%	9.3%	4.9%	1.1%
oil and gas extraction[a,b]	125,951	52.9%	28.3%	6.3%	1.8%
mining[a,b]	32,232	47.2%	38.8%	7.6%	1.3%
electricity generation[a]	40,488	8.0%	3.5%	17.7%	10.4%
construction	191,132	0.2%	0.2%	2.0%	0.4%
other manufacturing	395,632	47.7%	50.7%	1.2%	0.2%
pulp and paper manufacturing[a]	45,493	39.7%	27.2%	6.8%	0.7%
chemical product manufacturing[a]	80,153	48.3%	53.6%	12.1%	2.6%
industrial mineral product manufacturing[a]	13,599	22.5%	30.7%	6.9%	1.7%
metal product manufacturing[a]	78,644	44.8%	44.5%	4.4%	3.0%
wholesale and retail trade	226,700	9.2%	2.1%	2.8%	0.5%
transportation	142,492	19.2%	8.3%	7.3%	1.6%
private sector and non-profit sector services	796,186	8.8%	9.0%	1.7%	0.3%
government services	304,980	1.1%	0.8%	2.0%	0.3%
Total	2,596,009	20.0%	18.5%	3.7%	0.9%

[a] Indicates that the sector is treated as a large final emitter.

[b] Indicates that the sector is treated as an extractive sector.

As is common in applied general equilibrium analysis, a calibration procedure is adopted, where data on historical transactions in a benchmark year is used in combination with exogenous elasticity values to parameterize the consumer utility function and production functions. The year 2005 is used as the benchmark data year in the results presented here, but other years are tested to ensure the model results are robust to changes in specification of the benchmark year.

Parameter values to populate the model are drawn from a variety of sources. These values are generally similar to values assumed in applications of CGE models (Babiker, 2005; Böhringer and Rutherford, 1997; Paltsev et al., 2005). The elasticity of substitution between consumption and leisure is calibrated to give an uncompensated labour supply elasticity of 0.2, which is close to the average of the wide range of published estimates of this parameter (Evers et al., 2005). The elasticity of substitution between the fixed resource factor and other factors of production in extractive sectors is calibrated to give an own-price elasticity of supply of 1, which is the same assumption as used in other studies (Babiker, 2005; Paltsev et al., 2005).

Table 4.4: Model parameters

Parameter	Description	Value
Household utility function elasticities		
σ_t	Elasticity of intertemporal substitution	0.5
ε_{ul}	Uncompensated labour supply elasticity	0.2
σ_{eg}	Elasticity of substitution between electricity and natural gas	1
σ_{ht}	Elasticity of substitution between gas-electricity aggregate and petroleum products	1
σ_{ne}	Elasticity of substitution between non-energy goods	1
σ_{ne}	Elasticity of substitution between non-energy aggregate and energy aggregate	0.5
Production function elasticities		
$\sigma_{s,j}$	Elasticity of substitution between energy-value-added aggregate and material aggregate	0.3
$\sigma_{va,j}$	Elasticity of substitution between energy and value added aggregate	0.5
$\sigma_{ef,j}$	Elasticity of substitution between electricity and fuels	0.5
$\sigma_{cgl,j}$	Elasticity of substitution between coal and other fuels in electricity generation	0.5
$\sigma_{gl,j}$	Elasticity of substitution between natural gas and petroleum products	2
$\sigma_{kl,j}$	Elasticity of substitution between capital and labour	1
$\sigma_{in,j}$	Elasticity of substitution between intermediate non-energy material inputs	0
$\varepsilon_{f,j}$	Own price elasticity of resource supply	1
Trade elasticities		
$\sigma_{hf,i}$	Elasticity of substitution between home and foreign goods (Armington elasticity)	2.5-4
$\sigma_{dx,i}$	Elasticity of transformation between domestic and export markets	2.5-4
Dynamic parameters		
ϕ	Interest rate	0.039
δ	Depreciation rate	0.05

Chapter 5

Impacts of climate policy on the competitiveness of Canadian industry: How big and how to mitigate?[*]

5.1 Abstract

Competitiveness concerns have been at the forefront of national debates about Canadian climate policy, particularly as a result of its high energy intensity and significant exposure to international markets. This paper uses a dynamic computable general equilibrium model to assess the likely impacts on sectoral competitiveness that would accompany efforts to meet greenhouse gas mitigation targets that have been set by the Canadian government. Additionally, it evaluates several design mechanisms that could be used to reduce the negative competeveness impacts associated with adoption of domestic climate policies. The analysis suggests that several sectors would likely face significant competeveness challenges under a reference scenario in which permits are given to emitters in lump sum. However, it finds that competeveness impacts can be minimized by using output-based recycling of permits, or by using border tax adjustments.

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[*] An earlier version of this paper was presented at the International Association for Energy Economics 2009 conference in San Francisco, where it was selected for a Student Best Paper Award. The paper was published in *Energy Economics*, 2010, vol.32, pp. 1092-1104.

5.2 Introduction

International negotiations on climate change have progressed under the principle that nations face 'common but differentiated responsibilities' for greenhouse gas (GHG) emission mitigation (United Nations, 1992). As a result, it is likely that for the foreseeable future, emission reduction targets in developed countries will remain more aggressive than those in developing countries. Even within the group of developed countries, significant differences in the stringency of climate change policies may persist as countries adopt different emission reduction burdens, or as a result of particular national circumstances.

To the extent that more aggressive GHG abatement increases the cost of producing goods and services, persistent differences in policy stringency between countries could have important implications for competitiveness and for the effectiveness of the policies (Babiker and Rutherford, 2005; Fischer and Fox, 2007; Ismer and Neuhoff, 2007). First, differences in abatement efforts could lead to shifts in trade as corporations move production of carbon-intensive commodities away from more stringently regulated countries into less regulated countries. In turn, this could lead to loss of employment and economic output, and deterioration in the terms of trade in the more aggressively regulated countries. Fears of this type of competitiveness impact undermine the support for abatement policy in developed countries.

In addition to these economic impacts, a shift of production from the more stringently regulated country to less constrained economies can significantly reduce the environmental effectiveness of the policy. Since the greenhouse gases responsible for climate change are a global pollutant whose effect is independent of location of emissions, simply shifting production from one country to another does not improve the environment. To the extent that firms shift location to avoid regulation, the environmental effectiveness of the policy is reduced. This phenomenon is usually referred to as emissions leakage.

The environmental effectiveness of sub-global policies can be further lessened because of the rebound effect. As consumption of fossil fuels decreases in the stringently regulated country, world demand for fossil fuels falls, which should result in a reduction of their price. In turn, this should lead to additional consumption of fossil fuels in less regulated countries, which increases global emissions and further reduces the effectiveness of the policy (Felder and Rutherford, 1993).

These concerns over competitiveness and environmental effectiveness have slowed the implementation of climate policies in developed countries. If stakeholders in those countries feel that aggressive climate change abatement efforts are likely to reduce economic competitiveness without improving environmental outcomes, support for the policies will understandably diminish.

This paper focuses on competitiveness impacts of climate change policies in Canada. Competitiveness concerns have been at the forefront of national debates about Canadian climate policy. Canada's energy intensity of about 14 MJ per US dollar is significantly greater than that of the US (9.3 MJ/\$), France (7.0 MJ/\$), Japan (6.8 MJ/\$), and most other developed countries (Energy Information Administration, 2008). In addition, Canada's economy is particularly open to international trade. While total trade (the sum of imports and exports measured in units of domestic currency) is equivalent to roughly 70 percent of Canada's gross domestic product, it amounts to only about 55 percent in most European countries, and less than 30 percent for Japan and the US (Foreign Affairs and International Trade Canada, 2008). Canada's openness to trade and energy intensive economy mean that it could be especially susceptible to erosion of international competitiveness following imposition of carbon pricing.

Deterioration in the international competitiveness of energy intensive sectors, while potentially economically disruptive in any country, could be especially problematic in Canada's political system, which vests provincial governments with significant political authority. Because energy-intensive industries are not spread evenly throughout the country, a significant worsening of competitiveness could impose regionally uneven impacts, which would harm the acceptability of the carbon policy. For example, Alberta and Saskatchewan, home to most of the oil and gas industry in the country, as well as energy-intensive primary manufacturing sectors and much of Canada's coal-fired electricity generation, have greenhouse gas emissions of over 70 t CO_2e/capita, far higher than other provinces, which average about 15 t CO_2e/capita. Impacts on competitiveness created by a carbon policy would therefore likely be concentrated on these provinces.

The paper seeks to provide insight on two related questions. First, to what extent is competitiveness an issue for Canada's energy-intensive sectors in developing climate policy? Second, if competitiveness is an issue, what policies could Canada pursue that would reduce the impacts of domestic climate policy on the competitiveness of those sectors?

The paper begins by reviewing the literature on the competitiveness implications of environmental policy. A model used to evaluate impacts of carbon pricing on competitiveness is then described. Finally, the model is used to answer the two questions above. Because the first question has received more attention in the literature, the focus of the paper is on the second one.

5.3 Previous literature on the link between climate policy and competitiveness

Previous empirical work exploring the competitiveness implications of environmental policy has used both econometric and modeling techniques. Tobey (1990) provides an early econometric analysis. He employs a cross section and panel analysis to measure whether environmental regulation influences trade patterns in a sample of developed and developing countries. Neither approach yields estimates supporting the hypothesis that more stringent environmental regulations cause changes in net exports from a country. These results were echoed several years later by Jaffe et al. (1995), who surveyed over 100 empirical studies of the relationship between environmental regulation and international trade and found that 'Overall, there is relatively little evidence to support the hypothesis that environmental regulations have had a large impact on competitiveness'. More recently, researchers conducting ex poste analysis of the first phase of the European Union's Emission Trading Scheme failed to find a positive correlation between EU permit prices and imports of energy-intensive products from abroad (Baron et al., 2008). At least in part, these findings could be due to the fact that data to support econometric studies of the link between competitiveness and environmental policy is patchy, especially for developing countries that have significantly different environmental regulations than more developed countries.

In contrast to econometric studies, the numerical modeling studies that have explored sub-global greenhouse gas mitigation agreements like the Kyoto Protocol have typically found a strong link between competitiveness and the adoption of environmental policy. For example, using a standard multi-region static general equilibrium model, Babiker and Rutherford (2005) project that production of energy-intensive commodities in parties bound by the Kyoto Protocol would decline by about 2 to 5 percent relative to projected levels during the first commitment period, while production would increase in other countries. Impacts in Canada are projected to be higher; the same study suggests a 10 to 15 percent reduction in Canadian production and exports of energy intensive commodities following implementation of Kyoto. Using a similar multi-region static general equilibrium model, Wigle (2001) reports that Canadian production of energy-intensive goods would decline by roughly 1 to 5 percent if Kyoto targets were achieved. By changing some key assumptions in the basic model relating to trade elasticities and market structure, Babiker (2005) finds that these impacts could dramatically increase. In particular, by assuming that traded products are homogeneous rather than differentiated according to country of production, he finds that the competitiveness of heavy industrial manufacturing firms in countries bound by the Kyoto Protocol could decline by as much as 75 percent relative to projected future levels.

While most studies of competitiveness, including those described above, use general equilibrium models, others use a partial equilibrium framework. Such models allow additional detail on particular sectors, but omit general equilibrium feedbacks on competitiveness, which this paper suggests are important. In this vein, Fischer and Fox (2008) use a partial equilibrium model and find roughly 2 to 8 percent reduction in Canadian production of energy-intensive products associated with a modest (\$14/t CO_2) carbon price. Demailly and Quirion (2008) use a partial equilibrium model to suggest that a carbon permit price of \$20/t CO_2 would pose little problem for the international competitiveness of the European iron and steel industry, conventionally thought to be one of the most at risk from imposition of unilateral environmental policy (Hourcade et al., 2007).

Overall, the conclusion from the numerical modeling literature is that unilateral market-based carbon policies are likely to cause some reductions in the competitiveness of energy-intensive sectors in the regulated region. The results from the reference policy simulation presented later in this paper echo these findings. However, little research has focused on the types of policies that could be used to mitigate these competitiveness losses, while maintaining the environmental integrity of the policy. Hoel (1996) evaluates sector exemptions from a carbon policy, and concludes that these could help maintain competitiveness, but at a substantial cost to welfare. Fischer and Fox (2008) conduct a partial equilibrium analysis of border tax adjustments and output-based permit allocations, and conclude that both policies can help reduce competitiveness losses associated with unilateral carbon reductions.

However, no analysis has yet been conducted which offers a systematic comparison of the impact of alternative policies on industry competitiveness. Given the prominence of this factor in political discussions of carbon policy, such analysis is important, and is the focus of the current paper.

5.4 The model

A computable general equilibrium model is employed for analysis. While this approach means that particularities in some sectors may be glossed over to maintain model tractability, it offers several advantages over a partial equilibrium approach for this exercise. First, a general equilibrium approach allows for full adjustment of factor and commodity prices, as well as the foreign exchange rate, in response to an exogenous policy shock. As shown in the results, inclusion of general equilibrium feedbacks changes implications for competitiveness substantially. This is not surprising; as Krugman (1996) notes, ‘international trade is quintessentially a general equilibrium subject’. Second, a general equilibrium approach is able to ensure that government revenues are treated appropriately, and that fiscal neutrality is maintained, which offers an appropriate basis for comparing alternative policies, and also allows simulation of policies involving recycling of tax revenues. Finally, the general equilibrium approach allows estimates of welfare to be made, which provide the best measure of the overall effect of alternative policies.

The model is a single-region dynamic general equilibrium model of the Canadian economy. A forward-looking representative household is endowed with an exogenously increasing labour supply calibrated to an external forecast, and an initial capital stock that accumulates over time through endogenous savings and investment decisions. The household provides labour and capital services to firms, who combine these with intermediate material and energy inputs to produce commodities. Commodities can either be consumed domestically or exported to world markets under the assumption that Canada is a small open economy that does not affect world prices for commodities. A government agent is also specified, which collects all taxes in the model, and which produces an exogenously given level of government services, and transfers remaining revenue in lump sum to the household. Important aspects of the model are described in the following sections.

5.4.1 Household

The representative household is forward-looking, and chooses consumption to maximize discounted utility:

$$\max_{c_t} \sum_{t=1}^{T} \left(\frac{1}{1+\rho} \right)^t u(c_t) \tag{5.1}$$

where T is the time horizon of the model, ρ is the rate of pure time preference, c_t is full consumption (including leisure), and $u(c_t)$ is the instantaneous utility of consumption, given by:

$$u(c_t) = \frac{c_t^{1-\theta} - 1}{1-\theta} \tag{5.2}$$

where $\sigma_t = 1/\theta$ is the elasticity of intertemporal substitution.

Instantaneous consumption is based on a nested constant elasticity of substitution function, as shown in Figure 5.1, where σ_n is the elasticity of substitution for nest n. This structure imposes an endogenous labour supply in the model, as households are able to adjust their provision of labour in response to the after-tax wage rate. The parameter σ_{cl} is chosen so that the uncompensated labour supply elasticity in the model matches the exogenously given parameter ε_{ul}. The detailed nesting of energy commodities allows for realistic response of consumer demand in response to changing relative energy prices.

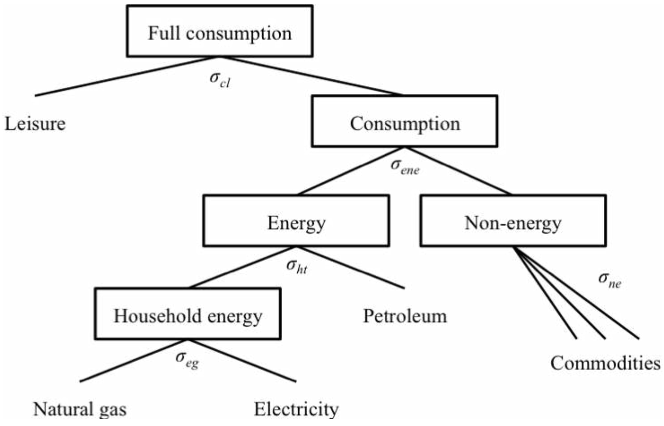

Figure 5.1: Nesting structure for household consumption

The consumer maximizes intertemporal utility such that the intertemporal budget balances:

$$\sum_{t=1}^{T}\sum_{i} p_{it}g_{it}(1+tc_{it}) = \sum_{t=1}^{T}\left(\frac{(L_t-l_t)w_t}{1+td_{lt}}\right)+TRN_t+\frac{K_0r_0}{1+td_{k0}}-\frac{K_Tr_T}{1+td_{kT}} \tag{5.3}$$

where p_{it} and g_{it} are the prices and quantities of good i in period t, tc_{it} are the taxes on final consumption, TRN_t represents lump sum transfers from government to households, L_t is the total labour endowment, l_t is the leisure consumption, w_t is the gross wage rate, td_{lt} is the direct tax on labour income, td_{kt} is the direct tax on capital income, r_t is the rental rate on capital, and K_t is the capital stock. The final two terms on the right hand side represent the value of the initial capital stock and the post-terminal capital stock, respectively.

5.4.2 Production

Production of goods in each sector j in each time period is given by a constant returns to scale, constant elasticity of substitution function, with nesting designed to represent detailed substitution possibilities between different fuel types, and between energy and value added. The nesting structure is given in Figure 5.2, where σ_m is the elasticity of substitution within nest m (sector subscripts have been dropped for clarity). At each level of the nest, producers choose inputs to minimize unit costs given the constant elasticity of substitution structure and the particular parameter choice for the substitution elasticity. For extractive sectors, a fixed resource input is required along with other factors of production. For these sectors, the elasticity of substitution σ_{ff} is chosen such that the own price elasticity of supply for the sector's output matches an exogenously-supplied elasticity, σ_f. The model does not address resource depletion issues, so that the fixed factor resource is available throughout the simulation period. Corresponding to the rectangular structure of Canada's input-output tables, the nesting structure allows multiple commodities to be produced by each sector. Choice of commodity production in each sector is governed by a constant elasticity of transformation function, with elasticity of transformation σ_t.

Producers maximize profits, and profits for each sector are zero in equilibrium:

$$\pi_j = p_jY_j - rK_j(1+tf_{jk}) - wH_j(1+tf_{jl}) - \sum p_{in}in_j \tag{5.4}$$

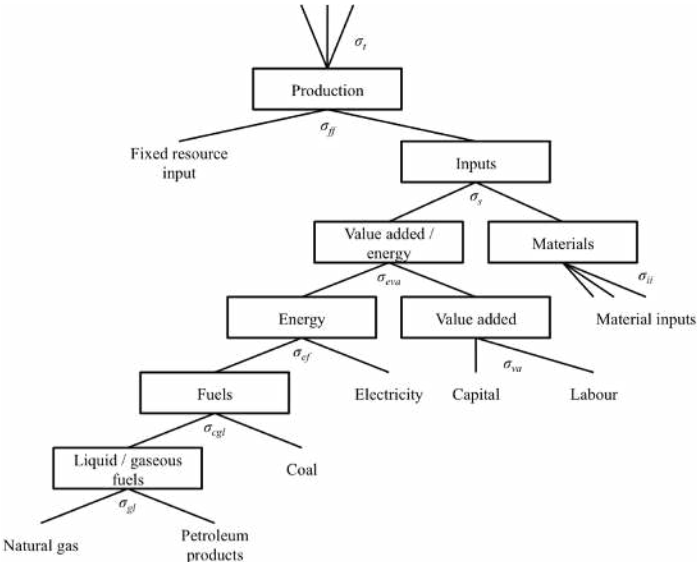

Figure 5.2: Nesting structure for firm production

where p_j is the price of output, tf_{jk} and tf_{jl} are the factor taxes rate on factors of production, p_{in} is the price of inputs, and in_j is the quantity of inputs.

5.4.3 Government

One government agent represents all three levels of Canadian government (federal, provincial, and municipal). Government collects net tax revenue (less subsidies), including both direct and indirect taxes. Taxes included in the model are (1) a direct labour income tax and (2) a direct corporate income tax, (3) an indirect factor input tax/subsidy on producers, (4) a consumption tax on final consumption and investment, and (5) import tariffs. The rates of all indirect taxes and subsidies are calibrated to the input output data, while the rates for direct taxes are derived from separate data on direct income taxation. All taxes are assumed to remain constant throughout the simulation unless endogenously modified (as described in the text). When a carbon price is applied, government is considered the owner of emission permits (or the collector of tax receipts, in the case of a carbon tax) unless otherwise noted.

Government expenditures finance provision of an aggregate public good (health, education, defense, etc.). In all simulations, provision of the aggregate public good remains constant at reference case levels. Remaining government budget is transferred to households in lump sum unless otherwise specified. Government is subject to an intertemporal budget constraint such that all net tax revenue is balanced by expenditures and transfers.

5.4.4 Trade

To allow for cross-hauling, the model uses an Armington formulation for international trade in which domestically and internationally produced goods are treated as imperfect substitutes. In particular, each domestic consumption good i is a constant elasticity of substitution aggregate of domestic and foreign goods:

$$A_i = \left(\alpha_{hf,i} h_i^{\gamma_{hf,i}} + (1 - \alpha_{hf,i} f_i^{\gamma_{hf,i}}\right)^{1/\gamma_{hf_i}} \tag{5.5}$$

Where A_i is the Armington aggregate, h_i and f_i are the quantities of domestic and foreign good, respectively, α_{hf} is a constant determined through calibration, and where $\sigma_{hf,i} = 1/(1-\gamma_{hf,i})$ is the Armington elasticity. For exports, a similar constant elasticity of transformation is applied to each domestic production industry:

$$Y_i = \left(\alpha_{dx,i} d_i^{\gamma_{dx,i}} + (1 - \alpha_{dx,i} x_i^{\gamma_{dx,i}}\right)^{1/\gamma_{dx_i}} \tag{5.6}$$

where d_i and x_i are the quantities of domestically produced good for domestic and export markets, respectively, α_{dx} is a constant determined through calibration, and where $\sigma_{dx,i} = 1/(1-\gamma_{dx,i})$ is the domestic-export transformation elasticity.

Trade in commodities is mediated through the foreign exchange market, which allows Canadian currency to appreciate or depreciate relative to foreign currencies.

5.4.5 Factor markets

Population is assumed to grow at an exogenous rate, determined by exogenous federal government forecasts of population. An exogenous labour productivity growth factor is applied to the population to generate an endowment of potential labour supply. As described in the section on consumer utility, the labour supplied to production is endogenous, since consumers can choose leisure consumption as a function of the real wage rate. Labour is treated as an aggregate, is assumed to be perfectly mobile between sectors, and the labour market is assumed to be perfectly competitive.

The capital stock owned by households in the first period is determined by calibration to the benchmark data set. Thereafter, the capital stock evolves endogenously, based on savings and investment decisions, as described in the following section. The initial capital stock owned by households is assumed to be sector-specific fixed capital. Vintages of capital installed during a model run are assumed to be perfectly malleable between sectors. Canada has access to the international capital market, where it can borrow or lend at an exogenous international interest rate, subject to an intertemporal borrowing constraint.

5.4.6 Dynamics

Consumers endogenously choose how much of total output to invest in a given period. The capital stock evolves subject to these investments:

$$K_{t+1} = K_t(1-\delta) + I_t \tag{5.7}$$

where K_t is the total capital stock in time t, δ is the rate at which the capital stock depreciates, and I_t is the total investment in period t. Overall investment is a constant elasticity of substitution aggregate of investment goods:

$$I = \left(\sum_i \alpha_{Ii} A_{Ii}^{\gamma_i} \right)^{1/\gamma_i} \tag{5.8}$$

where α_{Ii} is a calibrated constant, A_{Ii} is the quantity of Armington commodity i used for investment, and where $\sigma_I = 1/(1-\gamma_I)$ is the elasticity of substitution between investment commodities.

Investment is a ‘zero-profit’ activity:

$$r(1+\phi)I - \sum_i p_i A_I i(1+ti_i) = 0 \tag{5.9}$$

where ϕ is the interest rate, and ti_i is the ad valorem tax on investment demand for good i.

Because the model has a finite horizon, a constraint is needed for final period investment. Following Lau et al. (2002), the following constraint is used:

$$\frac{I_T}{I_{T-1}} \geq \sum_J \frac{Y_{J,T}}{Y_{J,T-1}} \tag{5.10}$$

5.4.7 Emissions

Greenhouse gas emissions are directly proportional to combustion of fossil fuels. Emissions policy is simulated by requiring all emitters of fossil fuels to hold a permit (or pay a tax) for each unit of greenhouse gas emitted. Because of the detailed nesting structure adopted, emitters have a choice of substituting between fuel types or improving energy efficiency in order to avoid emissions. Unless otherwise noted, emission permits are initially owned by government and are distributed to emitters in lump sum. The permit market is assumed to be perfectly competitive.

5.4.8 Data and calibration

Data on the financial flows underlying the model is derived from the annual economic accounts published by Statistics Canada (tables 381-0009 and 381-0010). The economic accounts data in Canada is structured as a rectangular matrix (in which each sector can produce multiple commodities), and this structure is maintained in the model development. The economic accounts data is supplemented with additional data on direct taxation (Statistics Canada table 385-0001), energy consumption (Statistics Canada tables 128-0002 and 128-0009), and greenhouse gas emissions coefficients (Natural Resources Canada 2006).

The model includes 16 sectors and 21 commodities. The level of aggregation is chosen to balance a relatively high level of useful detail with the computational requirements imposed by a dynamic model. Table 4.3 summarizes relevant data at a sector level. Overall, the energy value share in production is 3.7 percent, but there are several sectors for which production is much more energy intense: in particular electricity generation, petroleum refining, chemical manufacturing, and the agriculture sector. The table also illustrates the open nature of the Canadian economy, where roughly 20 percent of domestic consumption is imported and 20 percent of domestic production is exported. Some sectors - especially energy-intensive sectors - have much higher trade exposure than the average.

Table 5.1: Benchmark commodity data, 2005

	Export share[b]	Import share[c]	Trade share[d]	Energy share	Domestic output[e]	Domestic use[e]
Agricultural products	19.7%	17.2%	36.9%	11.2%	40,898	39,639
Products of primary industries[a]	12.2%	7.8%	20.0%	5.2%	15,498	14,753
Non-energy mining products	49.2%	38.6%	87.7%	7.3%	26,316	21,778
Coal	80.6%	79.6%	160.2%	7.6%	3,025	2,873
Crude oil	54.9%	47.0%	101.9%	6.3%	55,602	47,348
Natural gas	56.5%	12.5%	69.0%	6.3%	58,569	29,141
Manufactured food products	22.5%	21.5%	44.0%	1.4%	86,444	85,308
Other manufacturing products	56.2%	60.6%	116.8%	2.1%	369,762	410,510
Pulp and paper	40.4%	27.2%	67.7%	6.1%	56,902	46,590
Primary and fabricated metals	44.8%	44.2%	89.0%	4.3%	72,186	71,352
Chemicals	52.1%	62.7%	114.8%	11.8%	45,043	57,743
Cement and lime	21.8%	31.6%	53.4%	6.8%	12,382	14,159
Refined petroleum products	24.6%	13.5%	38.1%	15.2%	74,925	65,337
Construction				2.0%	190,004	190,004
Public and freight transport	20.9%	8.4%	29.3%	7.1%	131,673	113,683
Wholesaling	16.5%	0.7%	17.2%	3.2%	112,102	94,223
Services	6.2%	6.6%	12.8%	1.9%	822,024	825,268
Electricity	8.2%	3.5%	11.7%	17.5%	39,344	37,439
Water	3.3%		3.3%	2.2%	11,588	11,205
Retailing	0.3%		0.3%	2.8%	104,564	104,259
Government services	0.3%	0.0%	0.3%	2.0%	267,157	266,472
Total	20.0%	18.5%	38.4%	3.7%	2,596,009	2,549,085

[a] Includes hunting, fishing, and forestry, but excludes minerals.

[b] The export share is the percent of domestic production that is exported.

[c] The import share is the percent of domestic use that is imported.

[d] The trade share is the sum of the import and export shares.

[e] In millions of 2005 Canadian dollars.

As is common in applied general equilibrium analysis, a calibration procedure is adopted, where data on historical transactions in a benchmark year is used in combination with exogenous elasticity values to parameterize the consumer utility function and production functions. The year 2005 is used as the benchmark data year in the results presented here, but other years are tested to ensure the model results are robust to changes in specification of the benchmark year. Parameters used in the model runs, as well as the sources for the parameter values, are given in the Appendix.

5.5 Scenarios and results

To assess the competitiveness impacts that could be associated with unilateral implementation of aggressive climate change policy in Canada, I first consider a scenario in which a carbon price - imposed using either a cap and trade system with auctioned permits or a tax system - is applied in Canada on all combustion greenhouse gas emissions arising during both production and final consumption. No carbon price is levied on embodied carbon in exported goods. However, exporters are required to pay the carbon price on any emissions produced during the manufacturing process in Canada, or to absorb costs associated with emissions abatement. Because the carbon price is unilateral, foreign firms are not required to absorb such costs. This difference is what can generate impacts on the competitiveness of domestic firms.

In this scenario, revenues from the domestic carbon price are recycled in lump sum from the government to the household, such that government spending on public goods remains at reference case levels. The level of carbon price is set endogenously in the model to be consistent with achievement of 2020 emission reduction targets proposed by the federal government (Environment Canada, 2008; Government of Canada, 2008). These require a 20 percent reduction in emissions from 2006 levels by 2020, which likely represents a 30 to 40 percent reduction compared to business as usual levels in 2020. To allow the model to converge to a steady state, in years following 2020 the model requires that abatement remains at the same level relative to business as usual emissions as in 2020.

At an aggregate level, the results produced by the model are consistent with other analyses of Canadian climate policy. For example, in the scenario described here, Table 5.9 shows that the model suggests a welfare loss of about 1 percent due to the application of carbon pricing, and a loss of gross domestic product relative to projected business as usual levels reaching almost 3 percent in 2020 (this is the year of peak economic impact, and the impacts both before and after 2020 are less than this). This is consistent with the analysis by Dissou et al. (2002), who use a dynamic CGE model to assess the consequences of Canada achieving its Kyoto Protocol target, and with Wigle (2001), who uses a static CGE to assess the same target. Likewise, the level of carbon price, at about \$100/t CO2, is fairly close to the levels suggested in these studies and others (Bataille et al., 2006), once the relative stringency of targets is taken into account.

Table 5.2 shows the projected results of this policy on the competitiveness of Canada's productive sectors in a format similar to that used by Bruvoll and Fæhn (2006). Competitiveness is defined as the relative change in the ratio of world prices (pw) to prices at which domestic firms produce output (py), or $C = \frac{pw_1/py_1}{pw_0/py_0} - 1$. A negative value indicates that domestic firms have become less competitive compared to foreign firms, while a positive value indicates the opposite.

A change in relative prices can impact the market share of domestic firms in both domestic and international markets. The fourth column of Table 5.2 shows the change in the market share of domestic firms in the domestic market, which is dependent on values of Armington elasticities. The sixth column of the table shows the change in exports to world markets, which is governed by relative prices and the function that transforms domestic output into products destined for world and domestic markets. Overall change in domestic production, reported in the final column, depends on the change in domestic demand, the change in market share of domestic firms in the domestic market, and the change in exports. However, since the objective of the policy may be to curtail the size of the domestic market (e.g., fossil fuels), the overall level of domestic output provides a poor measure of the competitiveness impacts of the policy. Instead, this paper uses relative prices to indicate the impacts of the policy on competitiveness.

Table 5.2 shows two measures of the impacts of the policy on competitiveness using this measure of relative prices. The third column, labeled 'P.E. Comp.', shows the competitiveness impacts of the policy as calculated using the derived cost function for the sector in a partial equilibrium setting. In this partial equilibrium setting, I impose the carbon price, as well as any other exogenous policies (e.g., later in the paper I introduce a scenario where labour taxes are reduced in conjunction with the introduction of the carbon tax), but oth-

	Dom. Market	G.E. Comp	P.E. Comp	Dom. Share	Import	Export	Dom. Prod
Agricultural products	1.9	-4.1	-4.4	-1.4	13.3	-12.6	-2.8
Products of primary industries	7.7	-0.6	-2.1	-0.1	9.4	5.7	7.3
Non-energy mining products	-13.9	2.6	-2.4	3.0	-20.7	3.2	-3.2
Coal	-62.3	2.2	-2.4	40.9	-67.4	9.2	0.1
Crude oil	-38.3	2.5	-3.2	4.1	-43.0	-23.6	-28.2
Natural gas	-38.0	2.1	-3.2	1.9	-48.5	-21.5	-27.9
Manufactured food products	1.5	2.8	-0.4	1.1	-5.5	13.1	5.6
Other manufacturing products	-0.7	0.7	-0.7	1.5	-2.2	5.9	4.1
Pulp and paper	2.1	0.1	-1.3	0.1	1.7	2.9	2.5
Primary and fabricated metals	-4.9	-2.2	-2.9	-2.6	0.4	-17.5	-12.8
Chemicals	-26.0	-9.1	-4.7	-15.5	-14.2	-63.6	-53.9
Cement and lime	-6.1	-0.6	-2.5	-0.4	-4.8	-8.6	-7.2
Refined petroleum products	-27.7	-6.7	-6.8	-3.9	-2.6	-51.8	-36.3
Construction	-8.3						-8.3
Public and freight transport	-8.3	-3.9	-3.0	-0.6	2.6	-19.7	-11.4
Wholesaling	-2.7	2.2	-1.1	0.0	-9.0	4.1	-1.6
Services	-1.4	3.2	-0.6	0.3	-9.0	8.0	-0.3
Electricity	-5.4	-3.4	-7.0	0.1	-4.8	-6.2	-5.5
Water	-1.8					5.6	-1.5
Retailing	-0.4					7.0	-0.4
Government services	0.0	2.4	-0.6	0.0	-5.9	6.2	0.0

Table 5.2: Competitiveness impacts of carbon policy under lump sum recycling. In this and the following tables, Dom. Market is the percentage change in domestic use of the commodity (including intermediate and final use), G.E. Comp and P.E. Comp are the change in the relative price of domestic production relative to the world price in general equilibrium and partial equilibrium (see text), Dom. Share is percentage change in the domestic producer share of the domestic market, Import and Export are the percentage change in commodity imports and exports, and Dom. Prod is the percentage change in domestic production of the commodity.

erwise hold domestic prices of commodities, factors, and the exchange rate fixed. This is similar to what Jaffe et al. Jaffe et al. (1995) term a ‘theoretically desirable indicator of competitiveness’. This metric suggests that domestic production of all commodities will be less competitive as a result of the specified policy, with particular impacts on refined petroleum products, electricity, chemicals, and agricultural products. Domestic production of all commodities has worsened since the only price that has changed (in partial equilibrium) is the carbon price, which has increased.

While the partial equilibrium impact of the policy on competitiveness may be a theoretically desirable metric, it does not convey the likely actual outcome of the policy, since it omits general equilibrium impacts. For example, introduction of the policy is likely to cause adjustments in wage rates, domestic commodity prices, and the foreign exchange rate. All are important in determining how a policy impacts competitiveness. The second column of the table, labeled ‘G.E. Comp.’, illustrates the projected impact of the policy on competitiveness, this time in general equilibrium. Although all sectors are shown to be negatively impacted in partial equilibrium, this is not the case in general equilibrium. In particular, because of a reduction in the wage rate, a slight depreciation in the value of the Canadian dollar, and changes in commodity demand (see Table 5.9), several sectors, notably the service sector, which uses very little energy, actually become more competitive as a result of the policy. Conversely, because of increases in the prices of some commodities, which are intermediate inputs to production, the competitiveness impacts of other sectors are worse in general equilibrium than in partial equilibrium. The table shows that domestic producers of chemicals, refined petroleum products, and agricultural products have become substantially less competitive compared to foreign rivals; to a lesser extent, so have producers of electricity, transportation services, and primary metals. These commodities all have a high energy intensity (Table 4.3), which explains the increase in prices following imposition of the carbon policy. For products that are highly traded, like chemical products and primary metals, this increase in price translates into substantial loss in market share and output for domestic firms.

5.6 Addressing competitiveness impacts of climate policy

Based on the preceding analysis, there appears to be legitimate cause for concern that the most energy and trade intensive sectors of the Canadian economy could become somewhat less competitive relative to international firms in the event of the introduction of an aggressive Canadian carbon price in the manner described above. Fears of such impacts, and the corresponding losses in employment, could therefore undermine the support for carbon pricing in Canada, especially given the regional concentration of some of the exposed sectors. In addition, to the extent that production of energy intensive commodities shifts from Canada to other countries without a carbon price, the aim of the policy is partly subverted. When sub-global carbon pricing policies are considered, it therefore may make sense to consider policies to reduce the chance that production will shift to countries without a carbon price. Several measures are available that could reduce the competitiveness impacts of unilateral climate change policy. I discuss these in the following sections and use the model to evaluate their effectiveness in mitigating the negative competitiveness impacts found in the first scenario.

5.6.1 Revenue recycling

In the first scenario that was considered, revenues raised from carbon pricing were transferred directly from government to households. A frequently discussed alternative to lump sum transfers involves using revenue from carbon pricing to lower other taxes - for example the tax on income to labour or capital - while maintaining the real government budget constant. Most analyses suggest that this type of revenue recycling is likely to stimulate more economic activity compared to recycling in lump sum, because it can reduce the deadweight loss associated with existing taxation (Bovenberg and Mooij, 1994; Goulder, 1995). Some analyses even suggest, particularly at low carbon prices, that a fiscally-neutral carbon price with revenue recycling could stimulate economic growth overall (Bento and Jacobsen, 2007; Edwards and Hutton, 2001; Parry and Bento, 2000).

This type of policy is attractive because it is simple to administer, unlikely to conflict with international trade rules, and may improve the political acceptability of carbon pricing. However, although revenue recycling is likely to stimulate overall economic growth compared to lump sum transfers, it may not stimulate growth in those sectors that are particularly impacted by carbon pricing. Intuitively, a revenue recycling scheme will most help those sectors that are relatively intense in the factor in which taxes are cut, and which produce few emissions; by definition, these are unlikely to be those most impacted by a carbon price.

Table 5.3 illustrates the impact of imposing a carbon tax with labour tax recycling on the competitiveness of Canadian production. Although the labour tax rate is lowered by 6.2 percent as a result of this policy, this does not create advantages for domestic producers for which carbon pricing causes competitiveness problems, since these are not generally labour-intensive. Instead, by stimulating economic output, it causes increase in the carbon price (Table 5.9), which slightly exacerbates impacts in the sectors where competitiveness is already a problem. Conversely, in labour-intensive (service) sectors, competitiveness impacts were insignificant or positive in the original lump-sum recycling scenario, and recycling carbon revenues by cutting the labour tax creates a further benefit to these sectors. Overall, rather than reducing competitiveness impacts, the labour tax recycling policy appears to exacerbate competitiveness impacts (in general equilibrium).

	Dom. Market	G.E. Comp	P.E. Comp	Dom. Share	Import	Export	Dom. Prod
Agricultural products	2.7	-4.2	-4.2	-1.4	14.5	-12.1	-2.1
Products of primary industries	8.7	-0.6	-1.5	-0.1	10.4	6.7	8.4
Non-energy mining products	-13.6	2.6	-1.9	3.0	-20.5	3.6	-2.9
Coal	-62.3	2.2	-1.8	41.2	-67.5	9.7	0.5
Crude oil	-38.5	2.4	-3.1	3.9	-43.0	-24.6	-29.0
Natural gas	-38.2	2.1	-3.1	1.8	-48.2	-22.7	-28.7
Manufactured food products	2.3	2.8	-0.1	1.2	-4.8	14.3	6.6
Other manufacturing products	0.0	0.7	-0.4	1.5	-1.6	6.9	5.0
Pulp and paper	3.0	0.2	-0.8	0.1	2.5	3.9	3.4
Primary and fabricated metals	-4.2	-2.2	-2.5	-2.6	1.1	-16.9	-12.2
Chemicals	-25.7	-9.2	-4.4	-15.8	-13.7	-63.9	-54.0
Cement and lime	-5.6	-0.7	-2.1	-0.4	-4.2	-8.1	-6.6
Refined petroleum products	-27.6	-7.0	-6.8	-4.1	-1.3	-52.5	-36.5
Construction	-7.8						-7.8
Public and freight transport	-7.7	-3.9	-2.5	-0.6	3.3	-19.3	-10.9
Wholesaling	-2.0	2.3	-0.3	0.0	-8.6	5.1	-0.8
Services	-0.7	3.3	0.1	0.3	-8.5	8.9	0.4
Electricity	-4.8	-3.5	-6.7	0.1	-4.1	-5.6	-4.9
Water	-1.2					5.8	-0.9
Retailing	0.4					8.1	0.4
Government services	0.0	2.6	0.5	0.0	-6.2	6.5	0.0

Table 5.3: Competitiveness impacts of carbon policy under labour tax recycling

Table 5.4 illustrates similar results, but with revenue from the application of carbon pricing used to reduce the existing capital income tax. The reduction in this tax rate that maintains real government revenue constant was endogenously calculated to be 23.2 percent. When this policy is applied, investment is stimulated so the available capital stock is increased, which increases overall production, and so also increases the endogenous carbon tax relative to the lump sum scenario. This exacerbates competitiveness impacts on carbon-intensive sectors. Cuts in the capital tax benefit those sectors that are most capital intensive. The combined effect of these two dynamics results in the competitiveness impacts shown in Table 5.4. For example, manufacturers of crude oil, natural gas, refined petroleum products, and electricity are all extremely capital-intensive, and so cuts to capital taxation are beneficial to the competitive position of these sectors. In contrast, wholesalers and manufactured food products are less capital intensive, so cuts to the capital tax are much less beneficial to the competitiveness of these sectors.

Overall, while both types of revenue recycling can create aggregate economic benefits compared to lump-sum recycling, neither targets competitiveness impacts directly. Benefits to competitiveness as a result of these policies accrue to sectors that are relatively intense

	Dom. Market	G.E. Comp	P.E. Comp	Dom. Share	Import	Export	Dom. Prod
Agricultural products	2.5	-4.1	-4.0	-1.4	14.0	-12.0	-2.2
Products of primary industries	7.9	-1.1	-1.5	-0.2	11.1	4.2	7.2
Non-energy mining products	-8.4	3.1	-0.7	3.6	-17.0	13.7	5.4
Coal	-62.9	2.4	-0.5	46.4	-68.7	21.3	10.4
Crude oil	-38.0	4.4	0.0	7.4	-46.3	-9.1	-18.3
Natural gas	-37.4	3.6	0.0	3.2	-55.2	-4.9	-17.5
Manufactured food products	2.1	2.5	0.1	1.0	-4.2	12.8	5.9
Other manufacturing products	1.7	0.4	-0.2	0.8	0.8	5.5	4.4
Pulp and paper	2.5	-0.4	-0.8	-0.3	3.8	0.3	1.3
Primary and fabricated metals	-2.5	-2.5	-2.4	-3.0	3.6	-17.0	-11.6
Chemicals	-26.3	-9.6	-4.4	-16.4	-13.9	-65.3	-55.3
Cement and lime	-1.3	-0.8	-1.7	-0.5	0.5	-4.8	-2.7
Refined petroleum products	-27.9	-5.8	-6.8	-3.3	-6.5	-49.1	-35.4
Construction	-1.5						-1.5
Public and freight transport	-8.0	-4.7	-2.6	-0.8	5.4	-21.8	-11.8
Wholesaling	-0.7	1.4	-0.3	0.0	-4.7	3.5	0.0
Services	-0.1	2.8	0.4	0.3	-6.8	8.1	0.9
Electricity	-3.7	-2.6	-4.4	0.1	-3.2	-4.3	-3.8
Water	-1.1					5.4	-0.9
Retailing	0.6					7.1	0.7
Government services	0.0	1.5	-0.2	0.0	-3.7	3.7	0.0

Table 5.4: Competitiveness impacts of carbon policy under capital tax recycling

in the factor for which the tax is cut, which may or may not correspond to those sectors whose competitive position is worsened due to application of a carbon price.

5.6.2 Sector exemptions

Other types of policies do directly target the competitiveness impacts of carbon pricing. In countries that have implemented carbon pricing, sectoral exemptions are often used to protect internationally competitive industries from the policy. For example, Norway, which implemented a carbon tax in 1991, exempts the metals and cement sectors entirely from the tax, and offers much reduced tax rates for the pulp and paper sector and some other heavy industries (Bruvoll and Larsen, 2004). Sweden provided similar exemptions for industry in general, and in particular for energy-intensive industry, when it introduced its carbon tax in the same year Johansson (2006).

While this type of policy should be effective in preserving output and employment in the exempted sectors, it comes at a cost. Böhringer and Rutherford (1997) and Wigle (2001) suggest that sectoral exemptions from a carbon tax significantly increase the welfare cost of achieving a given emission reduction target in Germany and Canada, respectively, because the narrowing of the tax base means that the carbon tax has to rise significantly higher in other sectors. In addition, there could be practical difficulties associated with the implementation of sectoral exemptions, especially because information required by government to ascertain appropriate sectors to exempt from climate policy is difficult to obtain directly, and because the public may be opposed to sectoral exemptions in some cases. Hoel (1996) further notes that sectoral tax differentiation may be contrary to international trade laws.

Table 5.5 illustrates the projected change in competitiveness of Canadian sectors, given exemptions for the sectors with an energy intensity of at least 5 percent and a trade intensity of at least 50 percent (see Table 4.3). This definition includes the oil and gas, the mining, the pulp and paper, chemicals, and industrial minerals sectors. The results suggest, unsurprisingly, that sector exemptions are effective in preserving the competitiveness of exempted sectors. For example, although domestic chemical sector production is expected become much less competitive in the original lump sum scenario, if it is granted an exemption from the policy, it is likely to gain market share at the expense of foreign competitors, as a result of reduction in costs of other inputs.

	Dom. Market	G.E. Comp	P.E. Comp	Dom. Share	Import	Export	Dom. Prod
Agricultural products	-14.9	-11.7	-9.2	-4.1	14.9	-45.1	-25.2
Products of primary industries	-14.5	-4.7	-4.4	-0.7	-3.1	-26.1	-16.7
Non-energy mining products	-19.5	5.3	-0.4	6.3	-32.6	17.8	3.6
Coal	-67.6	2.6	0.0	52.7	-73.3	21.7	10.0
Crude oil	-59.1	9.6		18.3	-72.2	5.4	-16.1
Natural gas	-27.1	3.0		2.6	-44.4	2.5	-9.0
Manufactured food products	-6.6	-3.4	-0.9	-1.4	1.8	-18.3	-10.9
Other manufacturing products	-8.0	-0.2	-0.8	-0.3	-7.7	-9.3	-9.0
Pulp and paper	-5.7	1.0	-0.6	0.7	-8.5	-0.6	-3.0
Primary and fabricated metals	-21.6	-5.8	-4.9	-6.8	-10.1	-45.8	-37.0
Chemicals	27.7	4.0	-0.5	8.6	17.0	83.3	66.1
Cement and lime	-8.4	1.9	0.0	1.2	-12.2	-0.6	-5.3
Refined petroleum products	-32.9	-11.0	-13.5	-6.7	8.3	-65.5	-45.0
Construction	-8.9						-8.9
Public and freight transport	-17.1	-10.9	-6.2	-1.9	13.7	-43.4	-24.5
Wholesaling	-6.4	2.1	-1.9	0.0	-12.1	-0.2	-5.3
Services	-2.7	1.7	-1.3	0.2	-6.6	2.0	-2.1
Electricity	-0.7	-7.0	-9.3	0.2	0.8	-2.3	-0.9
Water	-3.0					4.5	-2.7
Retailing	-3.2					-4.8	-3.2
Government services	-0.1	1.5	-1.2	0.0	-3.6	3.6	-0.1

Table 5.5: Competitiveness impacts of carbon policy under sector exemptions

However, as has been found in the other studies referenced above, sector exemptions significantly exacerbate the overall economic impacts of the policy. Because the carbon price is required to rise higher owing to the narrower base for emission reductions, competitiveness impacts are amplified in non-exempted sectors. The higher carbon price also increases the overall negative impacts of the policy. Table 5.9 suggests that exemptions are likely to increase negative impacts on welfare, consumption, wages, and other key variables.

5.6.3 Output-based rebating

An alternative to sectoral exemptions is a policy in which the carbon price is applied to all sectors without exemptions, but where the revenue raised through carbon pricing is dynamically allocated to producers, thus changing incentives related to output quantity for profit-maximizing firms. This can be accomplished by allocating emission permits to firms according to an index of economic or physical output, or directly through a carbon tax accompanied by subsidies indexed to output. The policy provides similar incentives as a tradable emissions performance standard, and can be implemented as such (Fischer and Fox, 2007). The proposed Canadian policy regulating emissions from large industrial emitters is effectively a tradable emission performance standard (Government of Canada, 2008).

This form of policy preserves the incentive for domestic firms to reduce emissions associated with each unit of production, but eliminates the incentive for domestic firms to curtail production to meet emission targets. The introduction of output-based permit allocations introduces an additional distortion into the permit market related to the output subsidy, and may reduce the transparency of the policy to the public, but may help to preserve domestic production in the case where climate policy is implemented unilaterally, as is considered here (Bernard et al., 2007).

Several variants of output-based rebating schemes are possible. I consider a tradable performance standard system, in which government sets a baseline emission intensity for each sector, b_j. Firms that reduce their emission intensity below the baseline intensity create tradable credits, while firms that are unable to reduce emissions to the baseline intensity are required to purchase tradable credits to make up the gap. Under this policy, the sector cost function becomes:

$$c_j = c_j\left(p_K, p_L, \boldsymbol{p_E} + \boldsymbol{e}\tau, \boldsymbol{p_M}\right) - b_J\tau \tag{5.11}$$

where p_s ($s = K, L, E, M$) are the prices of inputs (bold fonts signify a vector), $\boldsymbol{e}$ is the emission intensity of energy inputs, and τ is the tax on carbon or permit price.

The policy-induced change in cost of production is therefore:

$$dc_j = \left(\frac{\partial c_j}{\partial p_K} dp_K + \frac{\partial c_j}{\partial p_L} dp_L + \frac{\partial c_j}{\partial \boldsymbol{p_E}} (\boldsymbol{e} d\tau + d\boldsymbol{p_E}) + \frac{\partial c_j}{\partial \boldsymbol{p_M}} d\boldsymbol{p_M} \right) - b_j d\tau \tag{5.12}$$

Application of Shepherd's Lemma gives $dc_j = (B_j - b_j)d\tau$, where B_j is the sectoral emission intensity in the absence of any policy. The incremental cost of a marginal increase in carbon price is therefore directly correlated with the baseline chosen by government (effectively the allocation of free permits). For non-marginal increases in carbon price, the change in sector costs depends on the parameters of the cost function - in particular the elasticity of substitution between energy and non-energy inputs (as well as between energy carriers), and the value share of energy in production - as well as the amount of credits that are allocated for free, b_j. A high elasticity of substitution means that firms can easily substitute other inputs for energy, or substitute low-carbon energy inputs for high-carbon energy inputs. If this is the case, then costs for the sector can actually decrease with output-based permit allocation (provided b_j is sufficiently large), implying that the firm can improve its competitive position, not only relative to the lump-sum recycling case, but also relative to the case where no carbon policy is applied at all. This dynamic is amplified for sectors where the value share of energy is high. Sectors where the value share of energy is high are exactly those for which competitiveness is an issue when carbon pricing is applied. If the elasticity of substitution is high in these sectors, this type of approach could effectively target competitiveness problems.

Table 5.6 shows the results of the carbon policy when output-based recycling is used. The dynamic recycling of revenue results in significant improvements to the competitive position of virtually every commodity for which competitiveness was originally a concern (in the lump sum recycling scenario). Sectors that produce these commodities typically have a high value share for energy, and so receive the bulk of the benefit from the output-based policy. Conversely, for sectors where little energy is consumed, the output-based policy results in worsening of competitiveness relative to the lump sum scenario (in general equilibrium). Overall, because the output-based policy directs the bulk of the carbon price revenues to sectors with high carbon emissions, competitiveness impacts are lessened compared to other policies. Additionally, as shown in Table 5.9, this policy stimulates more

	Dom. Market	G.E. Comp	P.E. Comp	Dom. Share	Import	Export	Dom. Prod
Agricultural products	-0.6	-1.9	-1.7	-0.6	4.3	-7.3	-2.7
Products of primary industries	1.8	-0.9	-0.7	-0.1	4.3	-1.1	1.3
Non-energy mining products	4.2	0.7	-0.7	0.8	2.0	9.2	7.3
Coal	-60.7	2.3	-0.7	43.0	-66.4	19.0	8.8
Crude oil	-33.1	0.5	-0.8	0.7	-33.9	-30.5	-31.3
Natural gas	-42.3	2.2	-0.8	1.9	-52.4	-26.5	-32.6
Manufactured food products	0.0	0.6	-0.1	0.3	-1.6	2.5	0.9
Other manufacturing products	-1.3	0.2	-0.2	0.4	-1.7	0.5	0.0
Pulp and paper	0.2	0.1	-0.4	0.1	-0.1	0.8	0.5
Primary and fabricated metals	12.0	4.0	1.9	4.9	0.6	46.5	32.9
Chemicals	-15.1	-3.7	-1.4	-6.9	-9.2	-37.3	-31.1
Cement and lime	-2.1	0.6	-0.1	0.4	-3.4	0.7	-1.0
Refined petroleum products	-25.5	-3.8	-2.6	-2.1	-11.6	-40.7	-30.7
Construction	-4.5						-4.5
Public and freight transport	-4.3	-2.5	-1.0	-0.4	2.8	-12.1	-6.4
Wholesaling	-1.2	-0.1	-0.3	0.0	-0.8	-1.6	-1.2
Services	-1.3	0.3	-0.2	0.0	-2.0	-0.5	-1.2
Electricity	10.5	12.2	14.1	-0.4	7.9	13.5	10.9
Water	-0.9					-2.7	-1.0
Retailing	-0.5					-0.4	-0.5
Government services	0.0	-0.2	-0.2	0.0	0.5	-0.5	0.0

Table 5.6: Competitiveness impacts of carbon policy under output-based permit allocation

output (GDP) than the lump sum recycling scheme.

5.6.4 Border tax adjustments

Finally, border tax adjustments have been discussed as a potentially appropriate way to reduce the leakage and competitiveness impacts of unilateral climate policy, both by scholars (Hoel, 1996) and by policy makers (e.g., recent proposals to regulate emissions in the United States). Export rebates could be used to protect the competitiveness of Canadian firms in international markets and import tariffs could be used to protect the competitiveness of Canadian firms in domestic markets. These adjustment schemes are likely to be effective in preserving the market share of Canadian firms, but it remains unclear whether they are compatible with world trade law (Babiker and Rutherford, 2005; Fischer and Fox, 2008; Ismer and Neuhoff, 2007; van Asselt and Biermann, 2007).

Practical implementation of border tax measures could also be challenging. Accurately measuring embodied carbon in imports and exports would be extremely difficult, especially in the case of heterogeneous commodities. Additionally, to the extent that such protectionist measures induce retaliatory measures by other countries, they could in fact reduce the competitiveness of Canadian firms, which are emission-intensive in comparison to most trade partners.

Despite likely implementation difficulties, Table 5.7 suggests that an import tariff could be effective in maintaining the market share of Canadian firms in Canadian markets following imposition of domestic carbon pricing. The policy is likely to be costly to consumers however, because it increases the price of imports, thus reducing consumption and welfare (Table 5.9). Additionally, the import tariff does not protect Canadian exporters abroad, so exports of many commodities continue to fall substantially even with tariffs on sales by foreign producers to Canada. Gross domestic product is accordingly reduced substantially with this policy.

	Dom. Market	G.E. Comp	P.E. Comp	Dom. Share	Import	Export	Dom. Prod
Agricultural products	-1.1		-4.3	-0.3	1.2	-15.7	-4.3
Products of primary industries	3.3		-2.1	0.0	3.6	1.5	3.1
Non-energy mining products	-13.5	3.3	-2.4	3.9	-22.3	9.5	0.9
Coal	-62.3	2.3	-2.4	43.7	-67.8	16.3	6.2
Crude oil	-36.0	2.7	-3.1	4.4	-41.3	-19.4	-24.7
Natural gas	-37.4	2.6	-3.1	2.3	-50.3	-16.4	-24.6
Manufactured food products	0.0	1.8	-0.4	0.7	-4.4	7.1	2.5
Other manufacturing products	-2.4	0.3	-0.7	0.7	-3.2	0.8	-0.1
Pulp and paper	-0.4		-1.3	-0.1	0.2	-2.7	-1.5
Primary and fabricated metals	-6.7		-2.9	-1.3	-4.1	-18.7	-13.1
Chemicals	-29.1		-4.7	-10.3	-21.7	-70.7	-55.4
Cement and lime	-7.1		-2.5	-0.1	-6.8	-9.4	-7.8
Refined petroleum products	-28.1		-6.7	-0.8	-23.3	-50.5	-34.0
Construction	-8.6						-8.6
Public and freight transport	-8.6		-2.9	-0.1	-6.6	-19.2	-10.9
Wholesaling	-4.0	2.9	-1.1	0.0	-11.8	4.7	-2.5
Services	-1.6	3.7	-0.6	0.4	-10.1	9.1	-0.4
Electricity	-6.2		-7.0	0.0	-6.1	-6.8	-6.2
Water	-2.2					6.8	-1.9
Retailing	-0.6					7.8	-0.6
Government services	0.0	2.5	-0.6	0.0	-6.0	6.3	0.0

Table 5.7: Competitiveness impacts of carbon policy under import tariffs

Table 5.8 illustrates the results of the carbon policy when export rebates are applied. In the table, the measure of competitiveness shows the domestic cost of production relative to the world price; the application of export rebates, which stimulates production and increases the carbon charge required to reach the carbon target, has worsened the competitiveness of domestic producers in domestic markets. However, once the tariff is applied, domestic producers maintain their competitiveness in international markets, such that exports fall less than in the lump sum policy. This helps to maintain overall production at slightly higher levels than the lump sum policy.

	Dom. Market	G.E. Comp	P.E. Comp	Dom. Share	Import	Export	Dom. Prod
Agricultural products	-0.4	-5.3	-5.1	-1.4	11.4	-2.7	-2.7
Products of primary industries	3.0	-1.4	-2.4	-0.2	6.5	2.7	2.7
Non-energy mining products	-12.4	1.7	-2.8	2.0	-17.0	-1.4	-5.5
Coal	-63.0	2.2	-2.7	39.9	-68.0	4.6	-4.0
Crude oil	-33.7	0.8	-3.6	1.3	-35.4	-29.0	-30.5
Natural gas	-39.6	1.9	-3.6	1.6	-48.5	-26.0	-31.3
Manufactured food products	0.2	1.4	-0.5	0.6	-3.4	6.0	2.3
Other manufacturing products	-2.1	0.4	-0.9	0.9	-3.1	1.9	0.8
Pulp and paper	0.0	-0.5	-1.5	-0.2	1.0	-0.3	-0.3
Primary and fabricated metals	-4.3	-2.8	-3.2	-1.9	-0.5	-7.3	-7.3
Chemicals	-15.5	-9.4	-5.4	-9.1	-7.8	-27.9	-27.9
Cement and lime	-6.3	-1.6	-2.9	-0.8	-3.7	-7.5	-7.5
Refined petroleum products	-26.4	-9.3	-7.8	-4.4	2.6	-30.7	-30.7
Construction	-8.1						-8.1
Public and freight transport	-6.1	-4.7	-3.4	-0.6	4.8	-7.1	-7.1
Wholesaling	-3.0	1.6	-1.3	0.0	-7.5	1.8	-2.2
Services	-1.5	2.4	-0.7	0.2	-7.2	5.4	-0.7
Electricity	-4.0	-4.4	-7.5	0.1	-3.1	-4.0	-4.0
Water	-1.7					2.9	-1.6
Retailing	-0.8					3.4	-0.8
Government services	0.0	1.7	-0.6	0.0	-4.1	4.2	0.0

Table 5.8: Competitiveness impacts of carbon policy under export rebates

5.6.5 Aggregate results

The previous sections have described the results of the various policy design options on the competitiveness of different sectors of the economy. Here, I briefly discuss aggregate results, rather than sector-specific results. Table 5.9 shows that the overall welfare impact of the policies is smallest for the revenue recycling options (although there is no ‘double dividend’ identified here). Both of these improve allocative efficiency compared to the lump sum case by reducing tax distortions. All other policies, including the border adjustments and the output-based allocations, increase distortions in the economy, and so worsen allocative efficiency, resulting in welfare losses. Gross domestic product is greatest in the output-based allocation scheme and the capital tax recycling scenario. Although competitiveness is not meaningfully discussed at a national level, the aggregate results do provide some insight into the competitiveness implications of the alternative design options. In particular, the price of foreign exchange is lowest in the output-based recycling scenario, suggesting a strong demand for Canadian exports. Likewise, the wage rate is highest in this scenario, suggesting a larger demand for labour than in other polices. Both of these metrics have been used by others as indicators of competitiveness (Boltho, 1996).

	Lump Sum	Labour Tax	Capital Tax	Import Tariff	Export Rebate	Exemptions	Output-based Allocations
Real CO2 Price ($/t CO2)	109.86	111.92	121.51	108.90	128.87	263.79	151.36
Equivalent variation	-0.62	-0.36	-0.40	-0.68	-0.70	-1.18	-0.65
Emission reduction	-37.75	-37.75	-37.75	-37.75	-37.75	-37.75	-37.75
Emission reduction, industry	-39.82	-39.87	-39.56	-39.78	-38.92	-34.51	-37.80
Emission reduction, household	-30.87	-30.72	-31.75	-31.01	-33.86	-48.49	-37.58
Labour supply (hours)	-1.28	-0.61	-0.82	-1.62	-1.27	-2.68	-0.27
Real after-tax wage rate	-3.40	-1.64	-2.19	-4.20	-3.52	-7.34	-1.45
Real exports	-5.64	-5.08	-4.20	-7.78	-4.69	-11.18	-5.75
Real imports	-6.22	-5.60	-4.59	-7.00	-6.34	-11.93	-6.12
Real price of foreign exchange	0.19	0.21	-0.30	0.09	-0.80	-3.70	-1.96
Real GDP	-2.81	-2.26	-0.83	-3.58	-2.42	-4.12	-1.79

Table 5.9: Selected results of policies to protect international competitiveness of Canadian industries, 2020. All values measured in percentage change from reference case scenario unless otherwise noted. All results are given for the year 2020 only, except equivalent variation. The carbon price is measured in 2005 Canadian dollars.

5.7 Conclusion

The Canadian government has committed to reducing greenhouse gas emissions by 20 percent below 2006 levels by 2020. Given its fast rate of projected population growth, economic growth, and growth in energy exports, high carbon prices will likely be required to achieve such targets. Concern has naturally been raised that these carbon prices could harm the competitiveness of certain Canadian industries, and especially of energy-intensive manufacturers and resource sectors.

The analysis in this paper reinforces the conclusion reached in other papers and by the public that aggressive Canadian reduction of greenhouse gas emissions, without similar action by other countries, could impinge on the international competitiveness of Canada's most energy-intensive sectors. In particular, the analysis highlights manufacturers of chemicals, refined petroleum products, primary metals, and agricultural products as those most likely to lose market share to foreign competitors following Canadian implementation of a carbon price. While these sectors are responsible for a fairly small share of overall economic output and employment, significant loss of international competitiveness in these sectors may still be politically unpalatable.

The analysis does suggest that design options are available which could significantly mitigate the competitiveness impacts associated with carbon pricing. In particular, output-based rebating of emission permit or tax revenue, which eliminates any incentive to curtail production as a way to reduce emissions, appears likely to significantly reduce competitiveness impacts of carbon pricing. While this design option does introduce an additional distortion into the permit market, significantly increasing the price of carbon necessary for a given level of emission reductions, it does not appear likely to damage welfare or economic output considerably. Additionally, output-based rebating, which is essentially the policy proposed by the Canadian government, is unlikely to conflict with international trade rules.

Other options can also reduce competitiveness impacts of carbon pricing, although not without significant tradeoffs. Sector exemptions from the policy, aimed at the sectors most likely to suffer loss of market share to foreign firms following carbon pricing, should reduce or even eliminate competitiveness impacts in exempted sectors, but concentrate the burden of carbon pricing on a smaller set of sectors, thus amplifying the impacts on these sectors, and weakening the economy as a whole.

Border tax adjustments also appear likely to significantly reduce the competitiveness impacts associated with climate policy, but not without considerable tradeoffs. Import tariffs, which raise the price of consumption in Canada, significantly reduce welfare and economic output. Export rebates appear more likely to improve welfare and economic growth in Canada; however, political and legal hurdles to both policies are likely to be large. In particular, it is unclear whether border tax adjustments are compatible with international trade law. Even if they were, adoption of border taxes could spur retaliatory measures that are damaging to Canadian competitiveness.

Finally, the analysis suggests that revenue recycling strategies, which use revenue raised from carbon pricing to cut labour and capital tax rates, are unlikely to preserve the international competitiveness of energy-intensive Canadian manufacturing sectors. These sectors tend to have lower capital and labour requirements than other sectors relative to energy consumption, such that benefits of cuts in taxation of these factors are outweighed by increases in price from carbon pricing. In contrast, less energy-intensive sectors may have their international competitiveness improved by this type of revenue recycling strategy. Importantly, however, revenue recycling, in particular to cut capital taxation, can significantly reduce the overall economic cost of climate policy. This finding is consistent with other studies.

While the analysis presented here describes the characteristics of each policy, it does not arrive at a clearly optimal policy for preserving the competitiveness of key sectors. Indeed, as highlighted in the general equilibrium analysis, policies that improve the competitive position of certain sectors often do so at the expense of other sectors and sometimes the economy as a whole. Ultimately, the choice of policy is a political one that balances these losses and gains against one another.

There are several important limitations of this analysis. Most importantly, a single-country model is used, and unilateral Canadian implementation of climate policy is assumed. In reality, although a fully global climate agreement is unlikely in the near future, some countries (e.g., European countries) have already implemented climate policies, and others are likely to follow in the near future. A fully global model would allow exploration of the impacts of several alternative scenarios surrounding international climate policy implementation, and the impacts on Canadian competitiveness. It is likely that if other countries, in particular the US, were to implement climate policy at the same time as Canada, competitiveness impacts shown here would be much reduced. An extension of this idea is that a particularly effective mechanism for mitigating losses in international competitiveness is to push for multilateral policy to reduce emissions.

Another limitation of the approach adopted here is the absence of incorporation of endogenous technical change into the model, which is increasingly being explored in general equilibrium models. It is unclear what effect this omission has on the findings offered here. Additionally, the model assumes perfect competition in all markets, which may not be appropriate, given the small number of firms in some sectors. Other analysis suggests that changing this assumption can affect the conclusions about international competitiveness (Babiker, 2005).

Despite the limitations, the results suggest that it is possible for Canada to implement climate policy unilaterally with fairly minimal losses to international competitiveness, by adopting carbon pricing policies with appropriate design options. In particular, output-based rebating of emission permits, which is the effectively government's current policy approach, appears likely to minimize competitiveness losses without contravening international trade rules. While this may not be the most efficient approach - using the revenues to cut existing taxes appears more likely to maintain economic output and welfare - it may be appropriate in the face of public hostility to competitiveness losses, and given Canada's uncertainty about carbon pricing policies that will be implemented by its trading partners.

Chapter 6

Distributional incidence of climate change policies in Canada

6.1 Introduction

Significantly reducing Canada's energy-related greenhouse gas emissions will likely require aggressive policies to encourage energy efficiency, low carbon secondary energy generation (from renewables, nuclear, or fossil with carbon capture), and/or fuel switching. There is much support amongst academics, as well as considerable momentum in the policy process, towards market-based approaches to implementing these policies, which involve directly or indirectly imposing a price on carbon emissions, either using a tax on emissions or an emission cap or performance standard system with tradable emission permits (Stavins, 2001). Given the scale of transformation envisioned - the federal government, for example, has endorsed a 17 percent reduction in emissions from 2005 levels by 2020, followed by more significant reductions in later years - the price on carbon emissions probably has to rise to quite high levels (National Roundtable on the Environment and the Economy, 2007).

A policy that imposed a large financial penalty on carbon emissions could be accompanied with significant distributional impacts - that is, it could concentrate costs in certain income or demographic groups. An understanding of the distributional impacts of climate policy is important, for two key reasons (Oladosu and Rose, 2007). First, from a normative perspective, policymakers are concerned with notions of fairness or equity in policy application. For example, guidelines for application of environmental policy issued by Canada's Department of Finance highlight 'fairness' as a key criteria in judging between alternative policies (Department of Finance Canada, 2005). Second, from a pragmatic perspective, a policy that creates a disproportionately negative impact on certain demographic or income groups is less likely to be viable, since concentrated impacts can be a cornerstone around which opposition to the policy can be mobilized (Olson, 1965).

Previously proposed and implemented market-based climate change policies in Canada have taken distributional consequences into account in policy design. For example, the introduction of British Columbia's carbon tax was accompanied by a 'Low Income Climate Action Tax Credit' paid to individuals and families defined as low income (British Columbia, 2008b).[1] Following lobbying by rural municipalities, British Columbia's government also initiated a 'Northern and Rural Homeowner Benefit', valued at up to $200 per year and starting in the 2011 tax year (British Columbia, 2010). Similarily, the 'Green Plan' proposed by the Liberal Party during the 2008 federal election included a carbon tax accompanied by measures designed to address possible distributional impacts of the policy. These measures included a boost to the Guaranteed Income Supplement, a new Guaranteed Family Supplement, and a low-income family Child Benefit Supplement, together valued at over $1.5 billion per year. Like the British Columbia carbon tax, the proposed federal carbon tax also included support for Northern and rural Canadians in the form of a Green Credit valued at $150 annually per household (Liberal Party of Canada, 2008). Similar support has been included in proposed US climate change policies. For example, the so-called Waxman-Markey bill of 2009 (H.R. 2454) allocated 15 percent of all allowances in the cap and trade scheme to low income households to mitigate negative impacts on this vulnerable population.

The primary objective of this paper is to assess the distributional consequences of plausible market-based climate change policies in Canada. The analysis is conducted with a computable general equilibrium model that distinguishes between a number of different classes of households, and which contains a significant amount of detail in its representation of the labour market. Simulations using the model show that the methods used to

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[1] The tax credit of $100 per adult and $31.50 per child applies to families earning less than $35,843 in 2010.

allocate permits and to spend revenues associated with a cap and trade system determine the eventual distributional incidence of the policy. In particular, a policy in which permit revenues are recycled to all households in lump sum is projected to benefit low-income households disproportionately, while a policy in which permit revenues are used to lower pre-existing income taxes is projected to benefit high-income households disproportionately.[2]

In addition to the primary objective, the paper has two secondary objectives. First, the paper aims to formally investigate the potential tradeoff between equity and efficiency in greenhouse gas mitigation policy design, a strand of research that has not yet appeared in the literature, and which is important given the above-noted emphasis placed by governments on maintaining fairness while applying market-based environmental policies. The analysis suggests that attempts to reduce societal inequality using greenhouse gas policy are likely to reduce overall economic output; the estimate in this paper is that using greenhouse gas policy to reduce the Gini index by one point is likely to come at a cost of roughly 1.2 percent of gross domestic product.

Second, the paper aims to provide an evaluation of methods that are used to assess the distributional impacts of environmental policies. It shows numerically that frequently used methods, including fixed-coefficient input-output analysis and methods that ignore producer response to carbon policies, are unlikely to yield accurate estimates of the distributional impacts of environmental policies. Further, it shows that a detailed representation of the labour market can be important in assessing these impacts.

The paper proceeds as follows. Section 2 is a summary of previous literature on the distributional incidence of carbon and energy policies, and also includes some discussion of the theory associated with the incidence of environmental policies. Section 3 outlines the model used for analysis. Section 4 describes the scenarios that were run using the model. Section 5 summarizes the results of the analysis, and section 6 concludes.

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[2] Analysis throughout the paper considers the implementation of a cap and trade scheme. As a number of authors have noted, when uncertainty and technological change are not present, cap and trade is analytically equivalent to a tax system. Thus the analysis in the paper applies equally to the case of a carbon tax.

6.2 Previous literature and theory

6.2.1 Tax incidence theory

When economists measure the distributional incidence of a policy, they are attempting to measure who bears the economic burden of the policy, or how the policy differentially affects the welfare of individuals throughout society. Analysis of the distributional incidence of policy changes - particularly taxes - is a fundamental area of research in public economics. Analysis of the distributional incidence of carbon policies can therefore build on a rich literature that has emerged from previous studies of the corporate income tax, the payroll tax, and various excise taxes (Kotlikoff and Summers (1987) and Fullerton and Metcalf (2002) provide excellent summaries of the economic literature on the incidence of taxes).

A carbon policy can influence an individual's welfare through several avenues. First and most obviously, by raising the prices of fossil fuels, it most penalizes those individuals that consume large amounts of fossil energy, and for whom there are no close substitutes for this consumption. Figure 6.1 shows the expenditures on fossil energy by household by income quintile as a proportion of current household expenditure and as a proportion of current household income. On average, households in Canada devote about 6 percent of their total expenditure to fossil fuels. However, there is some variation across different income levels. The lowest income households devote about 5 percent of the household budget to fossil fuels, while the middle income households devote closer to 7 percent, and the wealthiest households devote about 5 percent. A policy that raised the price of fossil energy might therefore be expected to impact more severely on middle income households than wealthly households or poor households. The picture is somewhat different when fossil fuel expenditures are compared to total income. In this case, poor households clearly spend a greater proportion of income on fossil fuels than wealthy households. Through this lens, any policy that raised the price of fossil fuels would be expected to bear most heavily on poor households.[3]

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[3] I show expenditures on fossil energy as a proportion of total current expenditure as well as as a proportion of current income because analysis by Poterba (1989) has suggested that using annual income as a basis for tax incidence calculations can be misleading if one is actually interested in the lifetime burden of the tax. Since individuals move between income categories throughout their lives, and since individuals can borrow

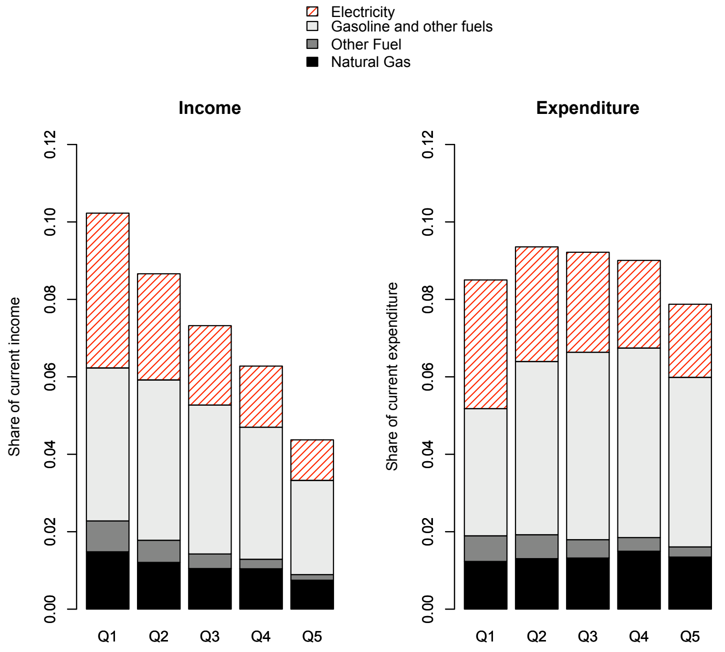

Figure 6.1: Household budget shares for energy, Canada, 2005. Source: Author's calculations using data from Statistics Canada, Survey of Household Spending, 2005.

A second way in which a carbon policy could influence an individual's well-being is by changing the prices of other goods and services purchased by the individual. For example, if the carbon policy increases the cost of producing certain goods, and if producers of these goods pass cost increases on to consumers, then consumers will experience increased prices not just for fossil energy, but for these other goods as well. An obvious example is electricity. Production of electricity produced over 100 million tonnes of greenhouse gas emissions in 2005 in Canada, as a result of burning coal and natural gas in fossil-fired power plants. A market-based policy that increased the cost of these fuels would therefore

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or save to smooth their consumption profiles over time, current-year income may be a poor proxy for lifetime income. While understanding the lifetime impact of a policy might be desirable, measuring lifetime income is difficult. Poterba, however, suggested that current-year expenditure is a reasonable proxy for lifetime income, because individuals can borrow or save when annual income deviates from annualized lifetime income, to smooth their consumption profile.

likely lead to increased cost of electricity generation, and increased electricity prices for consumers. Since individuals consume different amounts of electricity as shown in Figure 6.1, this opens up the possibility for differential impacts of the policy between households.

A third avenue via which a carbon policy can differentially impact the welfare of individuals is by changing their incomes. Incomes can change as a result of a carbon policy because firms may not fully shift the burden of the carbon policy onto consumers through higher product prices. As a result, some of the burden of the policy is borne by the factors of production employed by the firm - it's owners and workers. The simple partial equilibrium model in Figure 6.2 explains the mechanism (Kotlikoff and Summers, 1987). In Panel A, the point f defines the initial equilibrium in a commodity market in the absence of taxes. A tax on supply is imposed, which shifts the equilibrium to point e.[4] The producer price is now reduced from the original equilibrium price, while the consumer price is increased. The incidence of the tax is determined by the relative elasticities of supply and demand.[5] If consumer demand is perfectly inelastic (Panel B), producers will shift the entire burden of the tax onto consumers, so that the producer price will remain unchanged and the consumer price will rise by the full amount of the tax (the result is similar if producer supply is perfectly elastic). In contrast, if producer supply is perfectly inelastic (Panel C), the entire burden of the tax will be borne by producers (the result is similar if consumer demand is perfectly elastic).

Provided producer supply is not perfectly elastic and consumer demand is not perfectly inelastic, some portion of the policy will be shifted backwards onto factors of production, lowering the wage rate paid to the firm's workers and/or the return on capital earned by owners of the firm.[6] Since ownership of firms is concentrated in wealthy households,

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[4] An equivalent tax on demand would produce exactly the same impact.

[5] Formally, given equilibrium of supply and demand at the consumer price p and tax τ, $D(p) = S(p-\tau)$, we can differentiate to find $dp = \frac{\eta_S}{\eta_S - \eta_D} d\tau$, where η_i, $i = (S,D)$ is the elasticity of supply or demand. If the absolute value of the demand elasticity is large relative to the supply elasticity, the consumer price remains relatively unchanged, and the producer bears the burden of the tax. If the absolute value of the demand elasticity is small relative to the supply elasticity, the consumer price changes by close to the full amount of the tax.

[6] Although in a partial equilibrium framework, long-run marginal supply curves would generally be flat (so that all costs are borne by the consumer), in the general equilibrium analysis that follows, supply curves are upward-sloping because of the limited availability of primary factors of production.

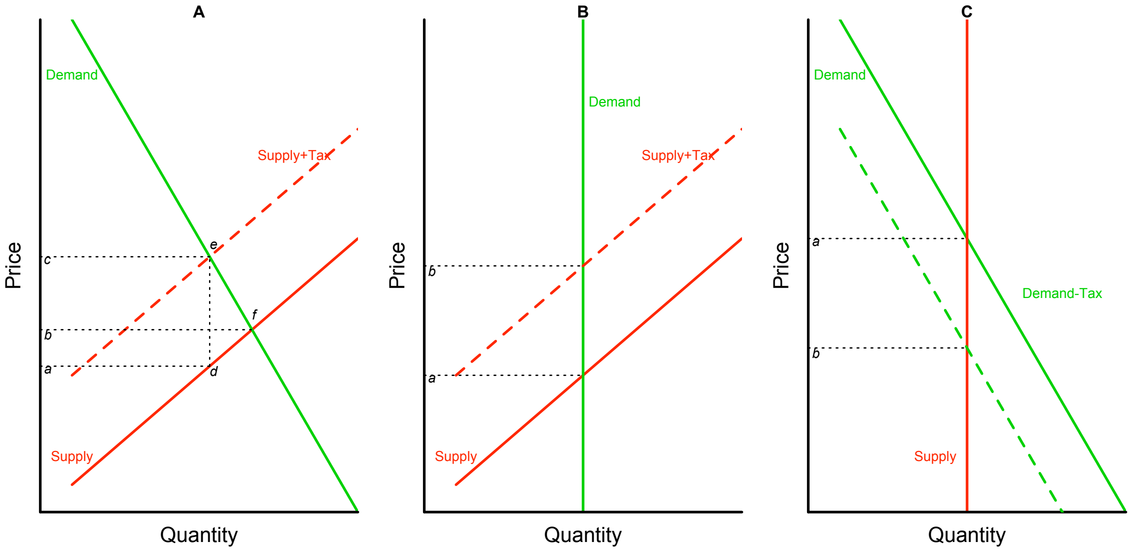

Figure 6.2: Incidence of a tax. Notes: Panel A shows the case where both supply and demand are not perfectly inelastic or perfectly elastic. In this case, the original equilibrium price is at b, and the consumer price after the tax is at e, while the producer price after the tax is at a. The loss in producer surplus from the tax is the polygon $abfd$ and the loss in consumer surplus is the polygon $bcef$. Tax revenues are given by $aced$. Panel B shows the case where demand is perfectly inelastic. In this case, the entire burden of the tax is shifted on to consumers, such that the consumer price increases from a to b, while the producer price remains at a. In Panel C, supply is perfectly inelastic. In this case, the entire burden of the tax is borne by producers, and the producer price falls from a to b, while the consumer price remains constant at a.

and since labour supply is different depending on household composition, this 'backward shifting' of carbon policy can itself have important distributional consequences.

Finally, a carbon policy could differentially impact the welfare of individuals if different individuals attach a different welfare value to the carbon policy itself through its environmental impact. For example, vulnerable populations (in Canada, this could include especially Northern inhabitants that derive substantial amenity value from the environment) could value carbon policy more highly than other populations.[7]

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[7] This source of difference is not further examined in this study because I hold the environmental impact

6.2.2 Previous studies

With the rising prominence of market-based approaches to climate change mitigation, there have been a number of attempts to estimate distributional impacts of such policies. Table 6.1 summarizes several of these, and groups them according to method. As shown in the table, most previous studies use an input-output model in combination with a consumer expenditure survey. The input-output model is used to propagate price impacts resulting from carbon pricing, which manifest themselves in higher fossil fuel prices, into indirect price impacts on goods consumed by consumers. Subsequently, these indirect price changes, along with direct price changes for fossil fuels consumed by consumers, are used with data from a consumer expenditure survey to estimate incidence of the carbon price.

In general, this type of study finds that the *absolute* incidence of carbon taxes in developed countries is regressive, meaning that poorer households experience a larger loss in relative income or consumption as a result of a carbon tax than wealthier households.[8] However, in less developed countries, analysis often suggests that the absolute incidence of carbon taxes can be progressive. These results arise directly from the shares of expenditure on carbon goods by households in consumer expenditure surveys. Since (in most wealthy countries) poor consumers spend a larger fraction of their income on carbon goods, it follows that carbon taxes will be shown to be regressive using this modelling approach. Using current year expenditure as a proxy for lifetime income, as suggested by Poterba (1989), can dilute or even reverse this trend; see for example Dinan and Rogers (2002) as well as Figure 6.1. Additionally, most studies suggest that while the absolute incidence of a carbon tax falls relatively heavily on poor consumers, the amount of revenue generated by the carbon tax is sufficient to offset this regressivity using targetted tax measures or lump-sum recycling; see for example Callan et al. (2009).

This approach, however, misses some important elements that can have significant im-

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of the policies fixed in the analysis.

[8] Three types of modeling studies are used to assess the incidence of a tax. In an *absolute* incidence analysis, revenues from the tax are ignored, so that only the incidence of the tax itself, and not the subsequent use of revenue, is assessed. In a *balanced budget* analysis, it is assumed that the revenue raised by the tax is spent by government. Since certain government programs and transfers can have a distributional impact themselves (by changing prices in various markets), this complicates the analysis of incidence (but makes it more realistic). Finally, in a *differential* analysis, it is assumed that the revenue is used to lower some other tax, which again complicates the simple estimates from absolute studies. See Fullerton and Metcalf (2002).

Table 6.1: Summary of literature findings on distributional impacts of environmental policies

Study	Finding
Input output model with consumer expenditure survey	
Metcalf (1999); package of various environmental taxes in US	Absolute incidence: regressive; Differential incidence: neutral or progressive
Brenner et al. (2007); carbon tax in China	Absolute incidence: progressive; Differential incidence: highly progressive
Dinan and Rogers (2002); carbon tax in US	Absolute incidence: regressive; Differential incidence: potentially progressive
Hamilton and Cameron (1994); carbon tax in Canada	Absolute incidence 'moderately regressive'
Callan et al. (2009); carbon tax in Ireland	Absolute incidence: regressive; Differential incidence: neutral
Lee and Sanger (2008); carbon tax in BC	Absolute incidence: mildly regressive; Differential incidence: potentially progressive
Econometric estimation of consumer demand system	
Tiezzi (2005); carbon tax in Italy	Absolute incidence: progressive
West and Williams III (2004); gasoline tax in US	Absolute incidence: regressive; Differential incidence: potentially progressive (with lump sum distribution)
West and Williams III (2004); carbon tax in Australia	Absolute incidence: regressive
Computable general equilibrium model	
Parry (2004); various environmental policies in US electricity (partial equilibrium model)	Differential incidence: highly regressive (with grandfathered permits) or mildly regressive (with lump-sum allocation to households)
Heerden et al. (2006); carbon tax in South Africa	Differential incidence: progressive
Araar et al. (2008); carbon policies in Canada (CGE model with stochastic dominance analysis)	Differential analysis: mildly regressive
Oladosu and Rose (2007); carbon tax in Susquehanna River Basin	Absolute incidence: slightly progressive; Differential incidence: highly progressive (with lump-sum permits allocation to households)

pacts on the incidence of the policy. First, neither consumers nor producers are able to respond to price changes by substituting among inputs. Since the purpose of a carbon price is to cause shifts in how products are produced and consumed, and since the ease of substitution among inputs impacts the welfare implications of a price change, this seems like a problematic assumption.

Second, these studies assume that all costs of the tax are borne directly by the consumer, and that none of the incidence of the tax is passed backwards onto factors of production. Since it is unlikely that consumer demand is perfectly inelastic or that producer supply is perfectly elastic, this is a problematic assumption. A better understanding of the incidence of a carbon tax would come from a model that explictly accounted for the possibility for producers to pass taxes backward to factors as well as forward to consumers.

A second approach to exploring the distributional aspects of environmental policy explicitly recognizes the ability of consumers to change decisions in response to changing prices, through the estimation of a consumer demand system. Both Tiezzi (2005) and West and Williams III (2004) estimate an almost ideal demand system based on a time series of household expenditure data disaggregated across household types. Cornwell and Creedy (1997) estimate a linear expenditure system based on similar data. Using this approach, they are able to model consumer response to the price changes from a carbon or gasoline tax, and measure welfare change using a true cost of living index. Tiezzi finds that the absolute impact of a carbon tax in Italy is mildly progressive, West and Williams find the opposite for a gasoline tax in the US, as do Cornwell and Cready for a carbon tax in Australia. These studies offer a significant improvement in some respects over the fixed-coefficient studies described above. By allowing consumers to respond to price changes by altering their consumption basket in a way that matches observed behaviour, they more closely capture the welfare impacts of price changes. However, as with the input-output approach, these studies do not capture the imperfect ability of firms to pass taxes forward onto consumers, and so do assume consumer income is fixed in response to policy changes. Further, these studies ignore producer response to environmental policies, which can be important in mitigating their ultimate impact.

Computable general equilibrium models, which allow the burden of a tax to be passed forward onto consumer prices or backward onto factors, and also model the process of adjustment to a policy by both producers and consumers, should offer a closer approximation of the welfare changes resulting from an environmental policy. A small number of CGE studies have been conducted to assess distributional consequences of climate change policy. Heerden et al. (2006) analyze a variety of environmental taxes in South Africa, with the aim of finding a combination of tax and revenue recycling scheme that simultaneously reduces poverty rates, increases economic output, and reduces emissions. Their model suggests that a carbon tax coupled with food tax reductions could achieve these goals. Importantly in this context, the model results are driven partly by dynamics in factor markets; by reducing food taxes, food production is encouraged. This sector has a large demand for elastically supplied unskilled labour, and so increasing output helps to reduce unemployment and also poverty rates.

Oladosu and Rose (2007) use a regional CGE model to assess the distributional impact of carbon taxes in the Susquehanna River Basin in the US. They conduct a balanced budget analysis and find that a carbon tax is slightly progressive. Again, dynamics in factor markets are an important component of their results: they find carbon-intensive industries are skilled labour intensive, such that carbon taxes reduce the skilled wage rate, which is paid predominantly to high-income households.

Araar et al. (2008) use a Canadian CGE model to measure changes in factor and commodity prices following a carbon policy. Subsequently, they undertake a stochastic dominance analysis by combining the price changes with data from a consumer expenditure survey containing over ten thousand households. They find that using proceeds from a carbon tax to reduce consumption taxes has a lesser impact on poverty rates than using proceeds to reduce labour taxes, and that either of these is superior to an output-based recycling scheme.

This paper contributes to the existing literature on the distributional impact of carbon policies in several ways. First, as shown above, it is one of just a handful of studies that use a computable general equilibrium model to assess the impact of carbon policies. Such models allow for a full range of impacts of carbon policies on income distribution. Second, it considers the labour market in more detail than other studies on the distributional incidence of carbon policies, both by including a specification for equilibrium unemployment and by disaggregating the labour market into a range of occupational categories. Finally, it adds to the existing body of empirical literature on distributional impacts of carbon policies, which is relatively sparse. This is important in itself, since as shown here, such policies can have potentially significant impacts on the distribution of income. As described above, the paper also sets out to systematically estimate the tradeoff between equity and efficiency in greenhouse gas policy, which has not been evaluated in previous studies. Finally, the paper aims to compare the results from the alternative methodologies described above, to determine how important is each of the various avenues in which a carbon price can influence welfare.

6.3 Model description

The model is a static, single-region, small open economy model that tracks production, private and government consumption, and trade. As in other such models, consumers make consumption decisions in order to maximize utility, subject to a budget constraint. In this model, multiple classes of consumers are explicitly specified, in order to provide an understanding of the impact of climate policy on consumers that differ in income and other demographic characteristics. Producers combine intermediate and primary factor inputs to produce output at minimum cost given a certain (exogenous) level of technology. The model differentiates 25 sectors, producing 55 types of commodities. Primary factors include capital, natural resources, and labour, with the latter further subdivided into 27 distinct employment classifications.

Because of the static nature of the model household and foreign saving are treated as exogenous. Likewise, the overall level of public good provision by government is treated as exogenous.

The following sections describe components of the model in more detail. Extra focus is given to factor supply, since the ownership of factors of production plays a significant role in determining policy incidence. A complete algebraic formulation of the model is included in the Appendix.

6.3.1 Sectoral production

Production in each sector is specified by a constant returns to scale nested constant elasticity of substitution (CES) function. Producers minimize (unit) costs subject to the specification of technology. The technology is shown graphically in Figure 6.3. At the top level, production is a CES function of a value added and energy aggregate and a Leontief aggregate of the K intermediate inputs. The value added and energy aggregate is a CES aggregate of value added and energy. Value added is a CES aggregate of capital and labour, with the latter a Leontief aggregate of M different employment types. Finally, the energy aggregate is a nested CES aggregate, with electricity, coal, natural gas, and refined petroleum products entering at different levels.

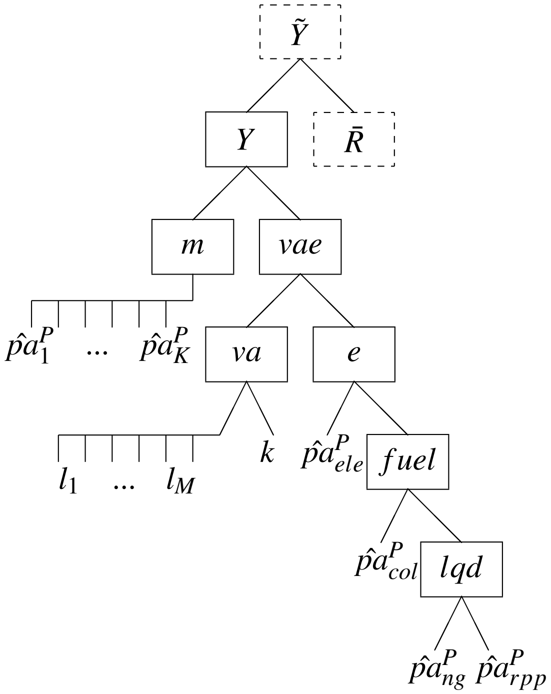

Figure 6.3: Nesting structure for production. Note: sectoral subscripts have been dropped to reduce notational clutter. The dashed boxes apply only to resource extraction sectors.

Overall output from each sector is is separated into different commodity groups according to a Cobb-Douglas transformation function. Parameters in the production functions are set to be similar to empirical literature and to other studies using similar models (for example, Wigle (2001), Paltsev et al. (2005), Dissou (2006)); parameters are shown in Table 6.2. For firms employing extant capital (see description below), elasticities are set to half of the values in Table 6.2.

Table 6.2: Production function elasticities

	variable	value
Between refined petroleum products and natural gas	σ_6^Y	1
Between coal and other fossil fuels	σ_5^Y	1
Between electricity and fossil fuels	σ_4^Y	0.5
Between value added and energy	σ_2^Y	0.5
Between primary factors	σ_3^Y	1
Between value added-energy aggregate and intermediate inputs	σ_1^Y	0.2

6.3.2 Transport, trade, storage, and tax margins

Various margins are associated with bringing each commodity to its destination market. These margins each drive a wedge between the producer price for a commodity and the price a consumer pays for the commodity. In particular, the model includes pipeline margins (for natural gas and crude oil), storage margins (for agricultural commodities), gas margins (for natural gas), and transport margins, tax margins, and wholesale and retail trade margins (for all commodities). Apart from tax margins, which accrue to government, margins involve the consumption of particular commodities and are supplied by appropriate production sectors. Margins are required in fixed proportions to commodity output, and are differentiated depending on the market (e.g., prices for final consumers are usually different than prices for intermediate consumption by producers).

6.3.3 International trade

The model treats Canada as a small open economy, meaning that import and export prices can be treated as exogenous. The so-called Armington formulation is used to account for cross-hauling, in which products originating in different regions are considered imperfect substitutes for one another. The Armington aggregate commodity is a CES composite of the imported and domestically produced commodity. For domestic production, a similar constant elasticity of transformation is applied to each domestically produced commodity, to determine how much of each good gets delivered to domestic as compared to international markets.

Values for the Armington elasticities in the model are based on those used in other analyses of trade and climate policies ((Babiker and Rutherford, 2005; Bohringer and Rutherford, 2002; Böhringer and Rutherford, 1997; Wigle, 2001; Dissou, 2005; Paltsev et al., 2005)). In particular, a value of 2.5 is used for all non fossil fuel commodities, and a value of 4 is used for fossil fuels. The domestic-export elasticity of substitution is set equal to the Armington elasticity.

6.3.4 Factor supply

Capital

Capital in the model is owned by households as well as by certain institutions that act as agents on behalf of households (mainly employer pension plans, registered retirement savings plans, and life insurance companies). Households in the model are endowed with an exogenous supply of capital, all of which is rented to productive sectors. Ownership of capital by household type is based on the 2005 *Survey of Labour and Income Dynamics* by Statistics Canada, which details income from investments by household type.[9] In addition, capital is supplied inelastically by institutions acting as agents on behalf of households. Since these institutions are agents acting on behalf of households, they do not appear as a separate account in the System of National Accounts. I include these institutions explicitly in the model because they allow me to capture lifecycle earnings more accurately as factor prices change in response to a policy. In particular, these institutions are funded mainly through contributions from labour earnings throughout an individual's working life (this is the bulk of 'Supplementary Labour Income' in the System of National Accounts), and provide income to an individual in retirement. By including institutions that act as agents on behalf of households as a separate account, I am able to capture these facts more accurately. I determined investment income for this group using additional data from Olson and Maser (2010).

Capital in the model is divided into two categories: 'extant' capital that is embodied

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[9] I verified ownership of capital by household using the 2005 *Survey of Financial Security* by Statistics Canada, and found very similar shares of per-household capital ownership as when I used the Survey of Labour and Income Dynamics.

in machines and equipment, and which is fixed in the production sector in which it is installed, and flexible capital that is available to be installed in any sector (this corresponds to a 'putty-clay' capital structure). I determine the percentage of 'extant' capital in the total capital stock according to $\left[\frac{1-\delta}{1+g}\right]^t$, where δ is the capital depreciation rate, g is the rate of economic growth, and t is the time period between when the policy is implemented and when the results are reported (so that $t = 0$ would give the short-run results of the policy and $t = \infty$ would give the long run results). Throughout the paper, I choose $t = 10$, to provide impacts of the policy with a 10-year time horizon. With $\delta = 0.05$, $g = 0.025$, extant capital makes up 46 percent of the total capital stock.

Capital is assumed to be immobile internationally, such that there is a fixed capital availability in Canada, and such that the rate of return in Canada can deviate from that in other countries.

Labour

Households are also endowed with an overall labour supply, specified according to employment category. They can choose to provide this to firms to increase income and consumption, or to 'consume' it as leisure. The choice between leisure and consumption is dictated by a constant elasticity of substitution function, with the elasticity of subsitution and distribution parameters chosen such that uncompensated and compensated elasticities of labour supply match empirical estimates, η_H and η_H^*, respectively.

In particular, the utility function of households is given by:

$$U = (\alpha C^\rho + (1-\alpha)L^\rho)^{1/\rho} \tag{6.1}$$

where C is aggregate consumption, L is leisure, and ρ and α are parameters to be calibrated. The budget constraint, using C as the numeraire, is given by:

$$C + wL = Y + wT \tag{6.2}$$

where T is total time available, $w = \frac{w_g}{1+t^L}$ is the net wage rate, w_g is the gross of labour tax wage rate, Y is non-labour income, and t^L is the tax rate on labour income. First order conditions are therefore given by:

$$\frac{\alpha C^{\rho-1}}{1-\alpha L^{\rho-1}} = \frac{1}{w} \tag{6.3}$$

Substituting equation (6.3) into the budget constraint (equation (6.45)), rearranging, and using the identity $H = T - L$, where H is time spent working, we obtain the Marshallian labour supply function:

$$H = T - \frac{Y + wT}{\left[\frac{(1-\alpha)}{w\alpha}\right]^{\frac{1}{\rho-1}} + w} \tag{6.4}$$

The uncompensated labour supply elasticity can be determined from this function as:

$$\eta_H = \frac{\partial H}{\partial w}\frac{w}{H} = \frac{(Y+wT)\left(\frac{1}{\rho-1}\left(\frac{1-\alpha}{\alpha w}\right)^{\frac{-\rho+2}{\rho-1}}\left(\frac{\alpha-1}{\alpha w}\right) + w\right) - Tw\left[\left(\frac{1-\alpha}{\alpha w}\right)^{\frac{1}{\rho-1}} + w\right]}{H\left(\left[\frac{(1-\alpha)}{w\alpha}\right]^{\frac{1}{\rho-1}} + w\right)^2} \tag{6.5}$$

The compensated leisure demand function, L^*, can be constructed by substituting the first order conditions (equation (6.3)) into the utility function (equation (6.1)). After some manipulation, this gives:

$$L^* = \frac{U}{\left(\alpha\left(\frac{1-\alpha}{w\alpha}\right)^{\frac{\rho}{\rho-1}} + 1 - \alpha\right)^{\frac{1}{\rho}}} \tag{6.6}$$

The compensated leisure demand elasticity can be determined from this function as:

$$\eta_L^* = \frac{\partial L^*}{\partial w}\frac{w}{L} = \alpha\left(\frac{1-\alpha}{w\alpha}\right)^{\frac{\rho}{\rho-1}}(\rho-1)^{-1}\left(\alpha\left(\frac{1-\alpha}{w\alpha}\right)^{\frac{\rho}{\rho-1}} + 1 - \alpha\right)^{-1} \tag{6.7}$$

The compensated leisure demand elasticity, η_L^*, can be related to the compensated labour supply, η_H^* elasticity as follows:

$$\eta_H^* = \frac{\partial(T-L^*)}{\partial w}\frac{w}{T-L^*} = \eta_L^*\left(1 - \frac{T}{H}\right) \tag{6.8}$$

Substituting equation (6.7) into (6.8) and recognizing that $\frac{\partial T}{\partial w} = 0$, we get an equation for the compensated labour supply elasticity. This gives a system of three nonlinear equations (equations (6.8), (6.5), and (6.3)) in three unknowns, T, α, and ρ.[10] These do not have a closed-form analytical solution, so the model includes code to provide a numerical solution, based on exogenous inputs for η_H and η_H^* as well as benchmark data on consumption, labour supply, tax rates, and non-labour income.

For values of η_H and η_H^*, I use estimates from the literature. Although values for parameters were not found corresponding exactly to the disaggregation of households used in this study, many studies do estimate these elasticities, and differentiate primarily between male and female labour supply.[11] Hum and Simpson (1994) report that estimates of male labour supply (in the US) made in the 1970s produced a mean value of about 0.1 for the compensated elasticity of labour supply, and an income elasticity of about -0.2. For females, the income elasticity was similar, but the compensated elasticity was estimated with a mean of about 0.9. These imply uncompensated elasticities of -0.1 and 0.7 respectively for males and females. This early literature suffered from a number of weaknesses, including neglecting non-linear budget constraints caused by non-proportional taxation, selection bias, measurement problems, and unobserved heterogeneity (Hum and Simpson, 1994).

More recent work directly addresses the participation aspect of the labour supply decision to deal with selection bias, uses an iterative process to deal with non-linear budget constraints, and uses new panel data sets to deal with unobserved heterogeneity. This new research typically finds similar labour supply responses for men. For women, the new research produces elasticities that vary fairly widely in range, but where compensated and uncompensated elasticities are generally somewhat smaller than those listed above. Addi-

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[10] Many analysts specify T exogenously, rather than calculating it. Common choices for T are 8,760 hours/year (all hours in the year) or some fraction of this quantity that removes time spent sleeping, and possibly time spent doing non-discretionary activities, such as eating and grooming. In doing so, they only need to input the uncompensated elasticity of labour supply with respect to wage rate, since the only unknowns are ρ and α. However, Ballard (1999) shows that this method often implies total income elasticities of labour supply that fall well outside the range of empirical estimates. He instead recommends a method similar to what I have done here.

[11] Econometric estimates of the income elasticity of labour supply, η_I, are often made. From a Slutsky decomposition, the uncompensated elasticity is equal to the compensated elasticity plus the product of the income elasticity and the share of hours worked in total hours available.

tionally, several randomized negative income tax experiments have been conducted in the US and Canada, which should yield more precise parameter estimates untainted by selection bias. In these experiments, Robins (1985) finds a mean compensated wage elasticity of 0.08 for men, 0.17 for married women, and 0.13 for single mothers, and a mean income elasticity of -0.10, -0.06, and -0.16 respectively for the three groups. Similar estimates were found in the Manitoba negative income tax experiment (Hum and Simpson, 1994). Additionally, it is noted that youth labour supply response to the negative income tax experiment was about double that for the rest of the population, and labour supply response for the rural population was higher than for the urban population (Robins, 1985).

Although the research has not converged on unique parameter values, a clear trend is that compensated elasticities are lower when work is less discretionary (as for men who were primary earners in the 1980s and earlier) and higher when work becomes more discretionary (as for some women in that era). The income elasticity is estimated relatively consistently throughout various demographic groups. In this paper, I assume an income elasticity of -0.15 for all groups, and a compensated elasticity of 0.2 for urban residents of prime working age (35 to 64). For rural residents, I add 0.2 to the compensated elasticity, and for youth and seniors, I add 0.4 to the compensated elasticity. This gives a population-weighted average compensated labour supply elasticity of about 0.35, which is within the range of the empirical literature (Blundell and MaCurdy, 1999).

Unlike many models of this type, which often treat labour as a homogeneous commodity, the current one dintinguishes between 27 different employment classifications. Each household type in the model is endowed with a specific combination of labour supply differentiated by employment category, and the wage rate in each labour market reaches a unique equilibrium. Since different sectors also require specific skills in combination as factor inputs, a policy that reduces the output of a given sector will also impact households that supply labour to the sector.

Standard consumer theory addresses the situation in which labour is treated as a homogeneous good that households supply provided the wage rate exceeds their reservation wage. Leisure is treated as a normal good with an opportunity cost equal to the wage rate. In the current model, where labour is treated as a disaggregate commodity, this approach requires some modification, since there is not a single wage rate, but rather a unique rate corresponding to each employment classification. The approach taken here is to endow each representative consumer with a number of time budgets equal to the number of employment classifications, and to allow a leisure demand corresponding to each employment classification, which in aggregate represent the total leisure consumed. This approach is possible because each representative household stands in for many individual households, each with their own time budgets.

In addition to the decision to consume leisure, the labour market model includes a representation of involuntary unemployment. I use the 'wage curve' specification, summarized in Blanchflower and Oswald (1995) to characterize the relationship between the real wage rate, w, and the unemployment rate, u.[12] In particular, real wages and the unemployment rate interact in the following manner:

$$\log \frac{w}{w_0} = \varepsilon_U \log \frac{u}{u_0} \tag{6.9}$$

where u_0 and w_0 are the benchmark unemployment and real wage rate, respectively.[13] The parameter ε_U is the 'wage elasticity of unemployment', and gives the expected change in the real wage rate resulting from a one percent change in the unemployment rate. Blanchflower and Oswald provide results from dozens of studies (including of Canada), and conclude that in diverse economies of different scales and in different time periods, the wage elasticity of unemployment is estimated remarkably consistently at about -0.1, meaning that a doubling in the unemployment rate is associated with a ten percent drop in real wages. Although Blanchflower and Oswald conceive of the causality in this relationship running from the unemployment rate to the real wage, in the model described here, the two variables adjust simultaneously until equilibrium is reached.

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[12] The scenarios examined in this paper use a 10-year time horizon. Over that period, it is possible that labour markets will clear, such that the representation of involuntary unemployment is unnecessary. However, I include it here on the assumption that there may be transitional impacts in the employment market even after the 10-year window following policy application. A more thorough examination of the effect of carbon policies on the rate of unemployment would require a dynamic model formulation.

[13] For parsimony, (7.3) does not include subscripts for occupational category. In practice the model allows both wages and unemployment rates to be different for different job categories.

Natural Resources

Finally, households and institutions that act on behalf of households are considered the owners of natural resources in the model and collect rent (net of resource taxes) from this ownership. Natural resources are modelled as factors in fixed supply, and are required by all extractive sectors, including: (1) Crop and animal production, (2) Forestry and logging, (3) Fishing, hunting, and trapping, and (4) Mining and oil and gas extraction. A separate class of natural resource is demanded by each sector. Lacking information on ownership of natural resources by household class, I assume a similar ownership structure to capital.

Natural resources, $\bar{R}$, are combined with other inputs in the production function Y, as shown in Figure 6.3, using a constant elasticity of substitution structure. The production function is calibrated to match an exogenously specified supply elasticity ε_R, which gives the percent change in output of the sector as a function of changes in price. The following calculations are required for this calibration process (these are similar to Rutherford (2002)).

The unit cost function is:

$$c(p_R, p_Y) = (\theta_R p_R^{1-\sigma_R} + (1-\theta_R) p_Y^{1-\sigma_R})^{\frac{1}{1-\sigma_R}} \tag{6.10}$$

where p_R and p_Y are the costs of resource and other inputs, σ_R is the elasticity of substitution between the resource input and the other inputs, and θ_R is the value share of resource rent in total production. Shepherd's Lemma gives:

$$\bar{R} = \tilde{Y}\frac{\partial c(p_R, p_Y)}{\partial p_R} = p_{\tilde{Y}}\left(\frac{\theta_R \tilde{Y}}{\bar{R}}\right)^{1/\sigma_R} \tag{6.11}$$

where I have used the fact that in a competitive market the cost is equal to the price of output, $p_{\tilde{Y}}$. Substituting this back into the cost function and rearranging gives:

$$\tilde{Y} = \bar{R}\theta_R^{\frac{1}{\sigma_R-1}}\left(1-(1-\theta_R)\left(\frac{p_{\tilde{Y}}}{p_Y}\right)^{\sigma_R-1}\right)^{\frac{\sigma_R}{1-\sigma_R}} \tag{6.12}$$

The exogenously specified resource supply elasticity relates the quantity of output to the relative price of output:

$$\varepsilon_R = \frac{\partial \tilde{Y} \frac{p_{\tilde{Y}}}{p_Y}}{\partial \frac{p_{\tilde{Y}}}{p_Y} \tilde{Y}} \tag{6.13}$$

Solving equations (6.12) and (6.13) and simplifying gives:

$$\sigma_R = \frac{\theta_R \varepsilon_R}{1 - \theta_R} \tag{6.14}$$

I assume that $\theta_R = 0.5$, implying that returns to natural resources are equal to one-half of the total operating surplus in each of the extractive sectors (with return on conventional capital making up the rest). Values of ε_R are set according to the literature. In particular, estimates for agricultural supply elasticities in the long run are often in the range of 0.3-1.2; I have used a mid-point value of 0.75 here (Rao, 1989). For mining and oil and gas, various estimates exist. Bohringer and Rutherford (2002) and Babiker (2005) both use supply elasticities of 1 for oil and gas and 0.5 for coal, but without providing empirical sources,. Krichene (2002) empirically estimates crude oil supply elasticities of 0.1 to 1.1, with a long-run average of 0.25, and a more recent average of 0.1. His estimates for natural gas supply are around 0.6 to 0.8. I use a value of 0.5 in this model.

6.3.5 Private demand

Consumer utility is given by a constant elasticity of substitution aggregate of leisure and consumption, as described above. Consumption is itself a nested CES aggregate of energy goods and non-energy goods, as shown in Figure 6.4. The non-energy goods nest is a CES aggregate of non-energy goods, while the energy goods nest is a constant elasticity of substitution aggregate of vehicle fuels (refined petroleum products) and household fuels, which is itself a constant elasticity of substitution aggregate of electricity and natural gas.

Following other literature ((Wigle, 2001), (Paltsev et al., 2005)), I set the elasticity of subsitution between non-energy and energy goods at 0.25, between various non-energy goods at 0.65, between transport and household fuels at 0.25, and between electricity and natural gas at 0.4. Importantly, I do not distinguish between the elasticities of substitution for different household classes. It is possible that households with different demographic characteristics have different substitution possibilities in response to a carbon policy. Lacking data on this, I do not include it, but it would be a fruitful area for future research.

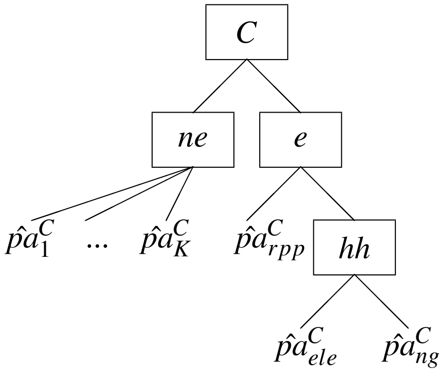

Figure 6.4: Nesting structure for consumer demand

Consumers in the model are assumed to maximize utility, as specified by the utility function detailed in Equation (6.44) and Figure 6.4, subject to a budget constraint. The consumer's budget is made up of several components, including income from labour, income from capital and natural resource endowments, income from pensions, and income from government transfers. The difference between income and expenditure is saving, and saving is fixed at the benchmark level in the model.

Tables 6.3, 6.4, and 6.5 shows benchmark levels of expenditure and income by source on a per-household basis, with households divided into income quintiles, age groups, and location of residence, respectively. Households in the highest income groups are the only significant savers; for other houses expenditures exceed income on average.[14] Additionally, the mix of income sources differs by household, with wealthier households deriving a larger share of their income from labour and investment and poor household deriving a bigger share of income from government transfers. A similar pattern holds for older households as well as for urban households. In contrast, poor households and elderly households derive a greater proportion of income from government transfers. Personal income tax rates differ significantly by household type as well. Households in the wealthiest quintile pay roughly 25 percent of gross income in taxes, while households in the poorest quintile pay less than 5 percent. All of these factors influence the effects of policies on household income, as well as the effects of policies on household labour supply. Finally, note that the energy share

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[14] I have divided households into income quintiles on the basis of total household income, not per capita household income. Since occupancy levels differ by household (see Table 6.3), this produces a different division than dividing on the basis of per-capita household income. Statistics Canada (2007) uses a similar method.

of total expenditure differs according to household class. Since the carbon policy directly affects energy prices, this is a further avenue for differential effects of the policy.[15]

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[15] The budget shares of energy are somewhat lower in Tables 6.3, 6.4, and 6.5 than in Figure 6.1. This is because the Tables use data corrected to match the System of National Accounts, where imputed expenditures on rent for owner-occupied dwellings are included, while the data in the Figure uses data directly obtained from the Survey of Household Spending.

Table 6.3: Benchmark household income and expenditure by income quintile

	Saving	Energy share	Expenditure	Gross labour income	Net labour income	Other income	Occupancy
q1	465	5.6	26127	17084	15400	11192	1.5
q2	-1442	6.9	40719	25868	20617	18659	2.1
q3	-2710	7.1	53512	43080	31687	19115	2.5
q4	-3030	7.1	69309	67719	48670	17610	2.9
q5	12239	6.4	104308	142162	99045	17501	3.4

Table 6.4: Benchmark household income and expenditure by age group

	Saving	Energy share	Expenditure	Gross labour income	Net labour income	Other income	Occupancy
under35	-3452	5.6	56541	61591	48530	4560	2.5
35to64	-1743	6.9	68132	76831	55686	10703	2.8
65over	16119	6.9	42357	18653	9579	48897	1.6

Notes: The columns ‘Gross lab income’, Net lab income’, and ‘Other income’ show sources of income, in dollars per household. Other income includes investment, pension, and government transfer income. The columns ‘Expend’ and ‘Saving’ show disposition of income, in dollars per household. The column ‘Energy%’ shows the share of total current consumption devoted to energy. The column ‘Occ.’ shows the occupancy rate of the household. Source: Calculations by author using data from Statistics Canada Survey of Household Spending, Survey of Labour and Income Dynamics, and System of National Accounts.

Table 6.5: Benchmark household income and expenditure by location

	Saving	Energy share	Expenditure	Gross labour income	Net labour income	Other income	Occupancy
urban	3007	6.3	61868	65782	47718	17157	2.5
rural	-10686	9.7	52926	37929	27289	14951	2.5

6.3.6 Government demand

All three levels of government (local, provincial, and federal) are modeled as a single entity which demands an aggregate public good (including health, education, defence, and other services). Except where specifically noted, the level of public good provision is held constant at the reference case level. Public goods are produced through the transformation of primary factors and intermediate inputs. In addition to spending on provision of public goods, government revenue is transferred to households in lump sum.

Government revenue is raised through taxation. The model distinguishes several different types of taxation: direct taxes on labour, capital, and natural resources, as well as indirect taxes on production and products. Indirect taxes on production are differentiated by sector, while indirect taxes on products are differentiated by product as well as by market. This system allows a detailed representation of the Canadian tax system, and allows the model to capture the interactive effects of existing taxes with proposed environmental policies, which has been shown to be important in studies of carbon pricing. Any surplus of government revenue over expenditure is saved (and invested).

6.3.7 Energy and greenhouse gas emissions

There are four distinct energy commodities in the model - natural gas, refined petroleum products, coal, and electricity.[16] Quantities of each of these energy goods are derived from the *Report on Energy Supply and Demand* from Statistics Canada and include manipulations to the input-output data to account for producer consumption of energy. Carbon coefficients for each of the fossil fuels are sourced from Natural Resources Canada. Combustion of refined petroleum products was responsible for about half of total combusion greenhouse gas emission in Canada in 2005, natural gas was responsible for about one third, and coal was responsible for the remaining one sixth.

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[16] Crude oil is treated as an intermediate input to the refining sector, where it is used to produce refined petroleum products. Other sectors use crude oil in smaller quantities. Crude oil is therefore not treated as an energy good in the model, but as an intermediate feedstock to production.

6.3.8 Model closure

Several assumptions regarding model closure are required. First, saving is treated as exogenous and fixed at the benchmark level. Although it is likely that climate policies will influence savings, in this static formulation, I abstract from the temporal dimension of savings, and so treat it as fixed. Second, the level of government provision of public goods is treated as exogenous and fixed at the benchmark level. Since application of carbon policies is likely to affect government revenues both directly (through creation of a new revenue source related to carbon taxation or pemit auciton) and indirectly (through changes in other tax revenues as economic activity adjusts), maintaining the level of government requires endogenous adjustments to other tax rates or transfers when carbon policies are applied. These endogenous adjustments are described in more detail in later sections of the paper. Third, the balance of trade is treated as exogenous and fixed at the benchmark level, implying an exogenous level of net foreign savings. This assumption effectively implies that the Canadian and international capital markets are not integrated, such that policies in Canada can cause the rate of return on capital to deviate from the international rate of return. Although this is a strong assumption, it the one generally applied in static CGE models (see e.g., (Springer, 2003)), since foreign saving has a clear temporal element that is difficult to address effectively in a static model. With both domestic saving and foreign saving fixed at benchmark levels, the overall nominal value of investment is also fixed in the model.

6.3.9 Data

A significant amount of data (as well as data manipulation) was required for this analysis. Underlying the model is data on aggregate flows between industries, government, and foreign and domestic consumers. The source for this data was the *System of National Accounts* (SNA) (from Statistics Canada). I used S-Level data, which breaks down production into 25 sectors and divides output between 59 commodities. S-Level data was chosen because it is the level most compatible with the disaggregation used in household spending surveys. I supplemented the S-Level data with energy data from M-Level tables, because S-Level energy data is not sufficiently disaggregated for the purposes described in this paper. Importantly, I used both Purchaser Price and Basic Price tables, which allow me to break down the margins that separate the two prices into detailed components including taxes, transport, and trade margins.

Data from the System of National Accounts does not disaggregate consumers into separate categories, instead treating all consumers as a single account. To disaggregate this account, I relied on two primary sources, both produced by Statistics Canada. The *Survey of Household Spending* (SHS) is an annual survey of about 15,000 households that are chosen to be representative of the population at large. It breaks down spending into about 150 spending categories. While there is a clear concordance in many cases with SNA commodities, in other cases, the concordance is less clear, and I used judgement to assign expenditures reported in SHS to the commodity disaggregation from the SNA. Perhaps the largest difference between the two sources related to their treatment of owner-occupied dwellings. The SNA 'imputes' a rental expenditure for these dwellings, which represents a substantial portion of total consumer spending in the SNA. In the SHS, imputed rent for owner-occupied dwellings is not calculated. I estimated imputed rent by household from expenditures on property taxes. Finally, while total reported household expenditure on commodities was usually close between the SNA and SHS, I scaled all SHS values to match totals from the SNA.

While the Survey of Household Spending was used to disaggregate total expenditures into individual households, the *Survey of Labour and Income Dynamics* (SLID) was used to disaggregate total income. The SLID consists of two panels, each containing roughly 17,000 households, that are designed to be representative of the Canadian population. The SLID details income by source, including investment income, pension income, transfer income, and labour income. Labour income is further disaggregated into 27 different employment classifications, as well as 25 sectors corresponding to the SNA. Income tax and social security contrbutions are also detailed on a household-by-household level, allowing for calculation of income tax rates differentiated by household category.

6.4 Scenarios

Using the model, I evaluate the overall economic and distributional impacts of two alternative greenhouse gas mitigation policies, chosen because they imply significantly different distributional impacts and because they have repeatedly surfaced in both academic and public policy fora. Both of the policies simulated are designed to be illustrative of the impact of government policy, and not designed to represent a particular policy package. In both policy scenarios, I consider a policy in which greenhouse gases are reduced by 25 percent from business as usual levels. This is similar to the required emission cut for meeting the current targets proposed by the federal government for 2020, and also similar to promises made by Canada during the Kyoto Protocol process. The division of capital between extant and new capital is chosen to represent a 10-year policy horizon.

Both of the policy scenarios analyzed are market-based greenhouse gas policies, in which government applies a cap and trade system that covers all combustion greenhouse gases in the economy.[17] In the first scenario, I assume that government auctions permits to emitters, and uses revenue raised from the auction to reduce the rate of personal income tax, such that the overall government provision of public goods remains fixed at benchmark levels.[18] This type of policy is widely discussed in the environmental economics literature, and is considered a 'tax shift' since an increase in an environmental tax is accompanied by an offsetting reduction in an existing tax. British Columbia's carbon tax was a tax shift in this vein. In the second scenario, I assume that government auctions permits to emitters, and transfers revenues raised from the auction directly to households in lump sum on an equal per-household basis (after saving enough of the revenue for itself to maintain constant the provision of public goods). This type of policy is sometimes referred to as a 'cap-and-dividend' or a 'Sky Trust', and has been raised several times in various public policy contexts. Supporters of this type of scheme justify it on the basis that each individual in society has equal claim on the environment, and therefore proceeds that accrue from charging for its use should be shared equally.

Because this is a single-region model rather than a global model, I consider the application of policy only in Canada. The resulting discrepancy in policy between countries could lead to changes in trade patterns, which I do not focus on in this paper, but which could have implications for the incidence analysis undertaken in the paper.

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[17] Although I refer to a cap and trade system, this is analytically equivalent to a tax on emissions. Different methods for allocating permits in a cap and trade system are likewise equivalent to different methods for distributing revenues in a carbon tax system.

[18] As such, this scenario (and the next) is a *differential* incidence analysis.

6.5 Results

This section begins by discussing the projected impact of policies on overall economic and environmental indicators, including output, labour activity, and emissions. Following this, there is a discussion of the distributional impact of the policies separated by household group. Finally, the results of sensitivity analyses that were conducted are reported.

6.5.1 Overall economic impacts

Table 6.6 shows the impacts of each of the policies on overall economic output and use of that output.[19] In the Tax Shift scenario, the real value of consumer spending increases by 2.2 percent, as a result of an increase in the real consumer wage induced by the cut in the personal income tax rate, which stimulates labour force participation. Spending on government provision of public goods and net exports are fixed in the model, so that the changes reported in Table 6.6 reflect changes in their prices relative to the price deflator, not changes in overall quantities. Spending on investment is determined substantially by exogenously specified savings, so that changes in investment reported in the table again reflect changes in relative prices. Overall, the Tax Shift policy is projected to have a positive impact on economic output. This outcome depends on the specification chosen for the labour market, and in particular on the inclusion of equilibrium unemployment in the model (Schneider (1997) explains how a double dividend is possible when unemployment is included in the model). I explore the dynamic of the labour market below. The carbon price in the Tax Shift scenario reaches about \$120/t CO_2.

In the Lump Sum policy, consumer spending is reduced by 0.6 percent in real terms, and the overall level of economic output is reduced by over 2 percent from the reference case. The significant reduction in economic activity in the Lump Sum scenario is consistent with other analysis and reflects what is known as the tax interaction effect (Goulder, 1995). In particular, by raising the price of consumption goods, the carbon policy augments the pre-existing labour tax, and reduces labour market participation. Without an offsetting tax shift, the cost of this tax interaction effect can be significant, as shown in Table 6.6. Clearly, the method for allocation of emission permits can have a significant effect on the magnitude

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[19] All economic values are reported in real terms, deflated by a Fischer price index (GDP deflator).

Table 6.6: Results of distributional analysis

	BAU	Tax Shift	Lump Sum
Gross domestic product			
Consumption		2.2	-0.6
Investment		-3.5	-9.2
Government		-1.1	0.6
Net exports		1.9	0.8
Total		0.2	-2.2
Labour market			
Gross wage		-5.7	-2.3
After tax wage		1.5	-2.2
Unemployment		-0.8	1.9
Employment		0.7	-1.6
Emissions			
Activity		-2.4	-13.1
Structure		0.3	-0.8
Intensity		-90.1	-77.5
Fuel mix		-24.5	-23.2
Household		-6.8	-8.8
Total		-123.5	-123.5
Carbon price			
Carbon Price		118.7	99.3
Gini coefficient			
Value	29.6	30.7	28.8
Change		1.2	-0.8

of economic impact of a carbon policy. In the Lump Sum scenario, the equilibrium carbon price is lower, reflecting the lower level of economic output. The carbon price obtained in this model is consistent with that obtained in other models.

The main labour market indicators are given in Table 6.6. I start by explaining dynamics in the labour market in the Lump Sum scenario, because they are somewhat more straightforward. In this scenario, both the gross and after-tax (net) wage rates are reduced, as is the overall level of employment. Conversely, the level of unemployment increases. The new equilibrium (lower wages, lower employment, higher unemployment) is a result of shifts and movement along both the labour supply and labour demand curves.

The left hand panel of Figure 6.5 illustrates the pre-policy (a) and post-policy (b) labour market equilibrium. When the policy is applied, the labour supply curve shifts outward, reflecting an increase in supply. This occurs because non-labour income - in particular income from investments - falls in the model simulation relative to labour income. The fall in the rate of return on investments occurs for two reasons: 1. Because labour is a relatively better substitute for energy than natural resources (which are a component of returns on capital), and 2. Because carbon-intensive sectors also tend to be capital-intensive sectors .[20] This reduction in the rate of return on investments lowers non-labour income for households. Since the income elasticity of labour supply is negative (implying that leisure is a normal good), reduction in non-wage income tends to shift out (increase) the household labour supply curve, as shown in the left hand panel of Figure 6.5.

While labour supply increases, labour demand is reduced as a result of the carbon policy. This occurs because the price on carbon lowers the marginal product of labour, which lowers demand for labour in a competitive market. The simultaneous shifts in labour supply and demand imply that equilibrium in the labour market moves from point a to point b in the figure, reflecting a lower level of employment and a lower wage rate.

As described earlier, this model adopts the wage curve hypothesis, which posits a negative relationship between the wage rate and the unemployment rate. Unemployment in Figure 6.5 is given by the difference between the dashed blue line and the solid black line; at a lower wage rate, the difference between the two lines increases. As a result, the reduction in the wage rate is accompanied by an increase in the unemployment rate. Initially, the labour market participation is given by L_0, the employment level is given by H_0, and the unemployment rate is given by $\frac{L_0-H_0}{L_0}$. After the carbon policy, the wage rate falls, increasing labour market participation to L_1 and increasing the unemployment rate to $\frac{L_1-H_1}{L_1}$. Overall, the policy reduces employment, increases unemployment, and increases the labour force

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[20] For a formal discussion of the impact of market structure and substitutability on the relative returns to capital and labour, see Fullerton and Heutel (2007) and Yohe (1979).

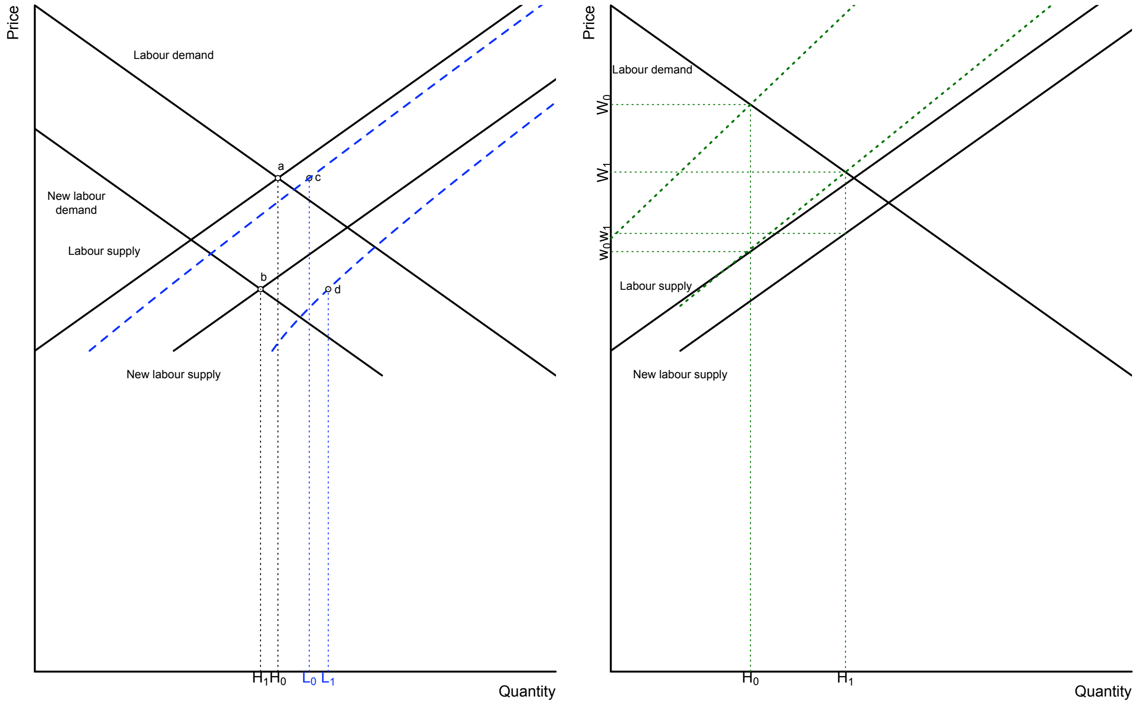

Figure 6.5: Impact of carbon policies on labour market

participation rate.

In the Tax Shift scenario, cuts in the personal income tax rate result in an reduction in the wedge between the wage rate paid by employers and that received by employees. Along with the reduction in non-labour income, which increases labour supply as described above, this results in an increase in the net wage rate for consumers, an increase in labour force participation, and a reduction in unemployment. These trends are shown in the right hand panel of Figure 6.5. In the figure, the dashed green lines show the labour supply with the labour tax, while the black upward-sloping lines show labour supply net of the labour tax. The increase in labour supply coupled with the reduction in the tax rate increases the net wage rate from w_0 to w_1, reduces the gross wage rate from W_0 to W_1, and increases labour market participation from H_0 to H_1.

Since wages are the largest component of income, the labour market impacts of the policy have important ramifications for household welfare.

6.5.2 Emissions

In each of the scenarios, combustion greenhouse gas emissions are reduced by an exogenously specified 25 percent, or 124 million tonnes of CO_2, from the reference scenario. However, because of different incentives provided by different policy designs, sources of greenhouse gas reductions differ by scenario. To show how, Table 6.6 decomposes the change in emissions in each of the scenarios into five terms using a logarithmic mean divisia index decomposition (Bataille et al., 2007; Ang, 2005). The decomposition methodology is available upon request.

In the table, the activity term describes how changes in the overall level of economic output affect emisisons; the structure term captures the impact of shifts in the economic structure of the economy on greenhouse gas emissions; the intensity term shows the impact of changes in energy intensity on emissions; the fuel mix term captures the impact of changes in the fuel mix; and the household term captures changes in household greenhouse gas emissions. In both scenarios, the bulk of the emission reductions come from changes in energy intensity, with fuel switching contributing substantially to overall emission reductions as well. Greenhouse gas changes from changes in the overall level of activity, from changes in economic structure, and from the household sector, are all much smaller.

6.5.3 Distributional incidence

Results

The discussion of distributional impacts of policies begins by showing the model projections of the welfare impact of policies according to household group in Figure 6.6. The charts decompose changes in welfare into direct effects resulting from the carbon policy (in red) and secondary effects resulting from the revenue recycling scheme (in blue). The effect of the carbon policy includes price changes on fossil fuels, price changes of other commodities, as well as income changes. The net effect of the carbon policy, including the recycling scheme, is denoted by the yellow arrow. Bars on the left correspond to the Tax Shift scenario, and bars on the right correspond to the Lump Sum scenario. In all charts, welfare is measured using the concept of equivalent variation as a percentage of income.

The top-left panel of Figure 6.6 shows how the simulated policies affect households

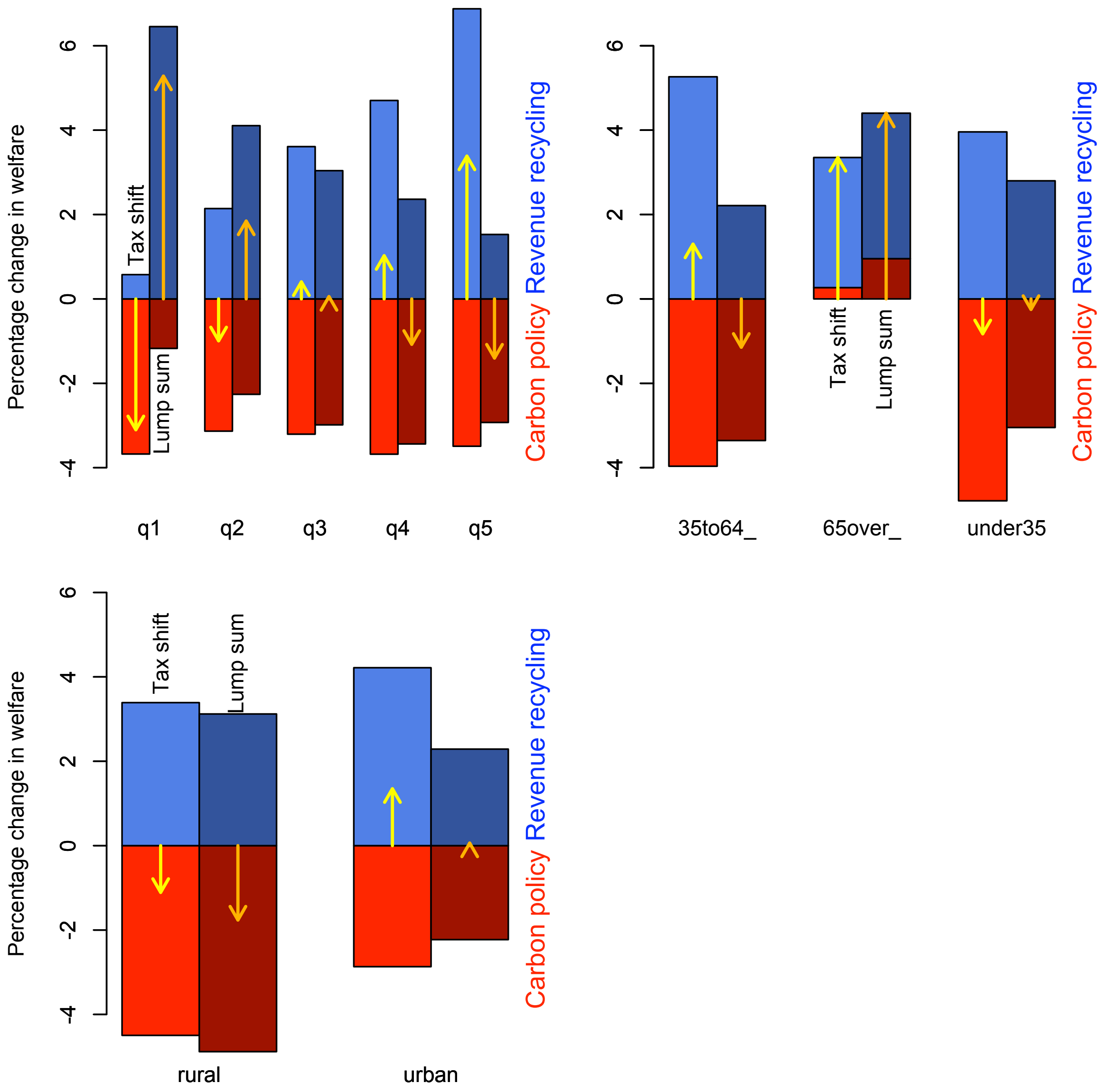

Figure 6.6: Distribution of policy impacts by age group, income, and location of residence

across the income spectrum. For each income bracket shown, the carbon policy has a negative direct impact on welfare. There is no clear pattern in the direct impact of the carbon policy across the income distribution. For the tax shift policy, the direct effect of the carbon policy is roughly equal across the income distribution, while for the lump sum scenario, the direct effect of the carbon policy is overall progressive (affecting the welfare of wealthier households more than proportionally compared to poorer households). As shown in the figure, the design of the policy (in the form of choice of revenue recycling scheme) has dramatic effects on the distributional impacts of the policy. In the Tax Shift scenario, where revenues from the carbon policy are used to reduce personal income taxes, the wealthiest households see a significant increase in welfare, while the poorest households see a significant reduction in welfare. This occurs because the poorest households pay very little income tax, so reductions in tax rates are not useful in offsetting the direct impact of the policy. In the Lump Sum scenario in contrast, low income households are disproportionate beneficiaries, since an equivalent transfer raises percentage welfare significantly more in low-income households. Other studies also suggest that lump sum transfers are able to mitigate most of the distributional impacts of a carbon policy.

The top right panel of Figure 6.6 shows the incidence of the policy according to the age of the head of household. Older households are projected to fare well under each of the policy scenarios, while younger households are projected to fare somewhat less well. It is particularly interesting to note that because a substantial portion of the income of wealthy households is fixed and invariant to carbon policy (for example, pension and government transfer income), the direct effect of the carbon policy is positive for these households. The relative difference between the Tax Shift and Lump Sum scenarios is greatest for prime age workers, who generate the greatest share of labour income, and who therefore benefit most from the cut in personal income tax.

The bottom left panel of Figure 6.6 shows the incidence of the policy according to household location. In the both scenarios, rural households are impacted more severely than urban households, especially as a result of their high share of energy expenditures and the fact that rural households rely especially on income sources in which rates of return fall under the carbon policy. In the Tax Shift scenario, urban households are projected to gain, since their much higher incomes mean that they are the primary beneficiaries of income tax cuts.

Figure 6.7 decomposes the direct impact of the policy (the red bars in Figure 6.6). To do so, I conduct a series of model runs in which I allocate all permit revenues to government, to isolate the direct impact of the policy. With this done, I conduct model runs in which I reallocate expenditures across households, such that the relative share of the budget spent on different commodities is set equal across all households (the absolute magnitude of household expenditures remains unchanged). This allows me to determine the welfare effect of the policy when households differ only by source of income. Following this, I conduct model runs in which the relative sources of income are set equal across all households (the absolute magnitude of household income remains unchanged). This allows me to determine the welfare effect of the policy when households differ only in how they allocate their budget. I also conduct runs in which both the household incomes and expenditures are unchanged.

Throughout the model runs shown in Figure 6.7 it is clear that the total impact of the policy is somewhat (and in some cases, much) better predicted by the income effect than by the expenditure effect. In other words, the distribution of the policy impacts are determined substantially by the way in which household incomes are derived, more so that the way in which households allocate their expenditures. This is most evident when examining the impact of policies across the distribution of age profiles. The black bars show the overall projected impact of the policy, and suggest that the policy would impact young and middle-aged households roughly equally, and benefit older households. When sources of income are held equal across all households, however - represented by the white bars - the policy appears to have virtually no distributional impact and is spread evenly throughout the population. This suggests that differences in shares of expenditures on energy and other goods between households are not important in explaining the incidence of the policy. In contrast, when household budget shares are held equal across households, the full distributional incidence of the policy is revealed to be due to differences in income sources. In particular, older households, which derive a substantial portion of income from fixed sources like government transfers are shown to benefit from a carbon policy (even without revenue recycling).

These results are especially important in light of the previous literature described earlier in this paper. In particular, nearly all previous literature focuses uniquely on how households allocate their budget, and neglects to consider how households source their income. Since this study shows that sources of income are probably a more important mechanism for transmitting distributional incidence than budget allocation, this is a worrying omission from previous studies. It also helps to explain why the few studies that use CGE models (including this one - see the top left hand panel of Figure 6.7) show that carbon policies can be progressive, even before revenue recycling has taken place.

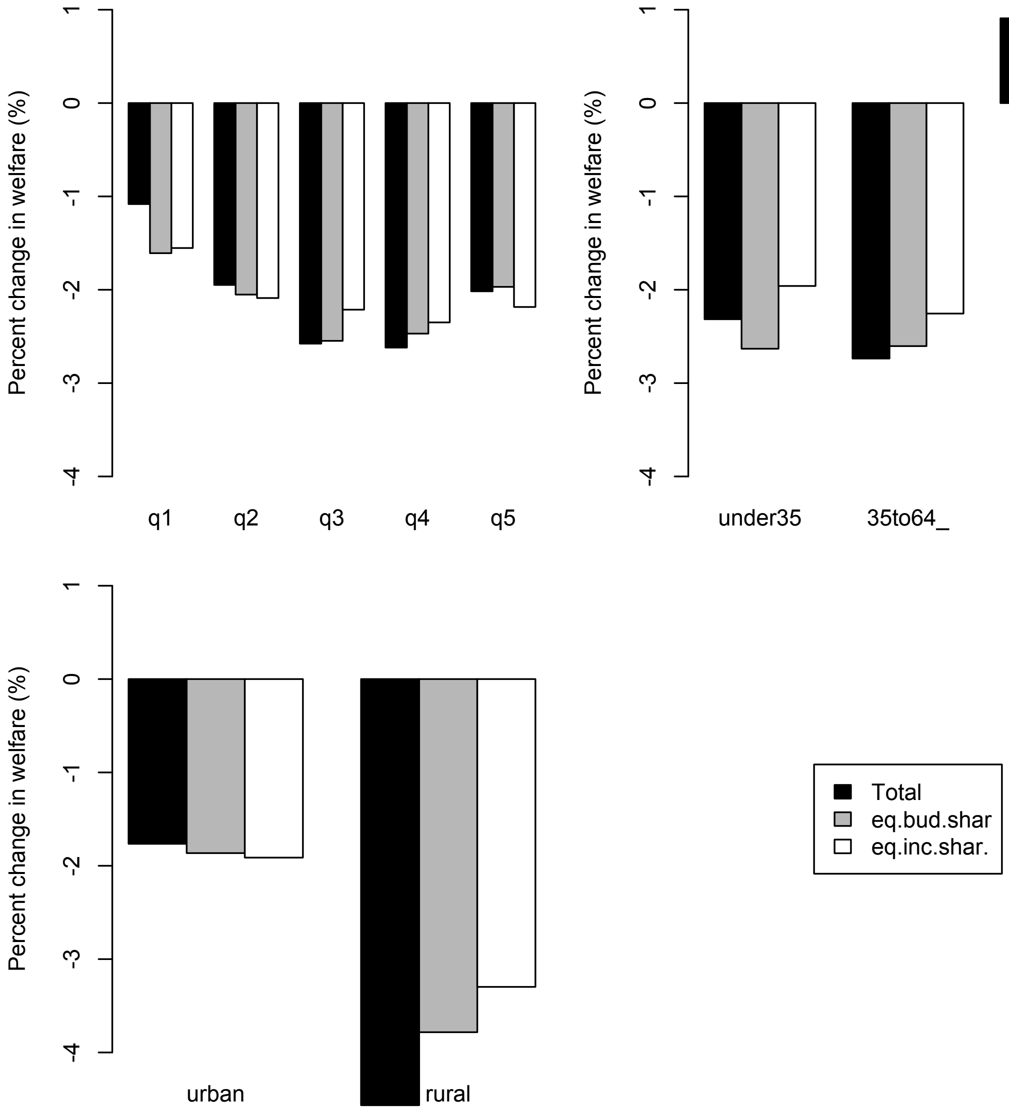

Figure 6.7: Decomposition of policy impacts by distribution

Although the results above provide a detailed indication of the incidence of the policy, it is useful to provide a scalar measure of changes in income distribution that result from alternative policy designs. A frequently used measure of income distribution is the Gini coefficient. This parameter can take on values between 0 and 100, with 0 indicating that wealth is evenly distributed throughout the population, such that each individual holds an identical share of total wealth, and 100 indicating that a single individual holds all wealth. The Gini coefficient ranges in value from about 25 in countries with a strong redistributive focus (Denmark) to about 60 in countries where inequality is pervasive (Brazil, South Africa).[21] The Gini coefficient in Canada in the benchmark data for 2005 is 29.6.

Table 6.6 shows the changes in the Gini coefficient that are calculated to result from the proposed policies. Increases in the coefficient show that inequality is increasing, while decreases show that the policy has increased equality. The two policy scenarios produce quite different impacts on overall income distribution, as already shown in Figure 6.6. The Tax Shift scenario is a regressive policy and increases the Gini coefficient by about 1.2 un1its or about 4 percent. The Lump Sum recycling scenario is a progressive policy, reducing the Gini coefficient by about 0.8 units or about 3 percent. As described earlier, previous analyses have also found that a carbon policy with lump sum recycling of revenues is a progressive policy.

Tradeoff between equity and efficiency

The previous analysis suggests that the design of a climate policy can have a significant impact on the distributional incidence of the policy. In particular, policies that use revenues from the auction of carbon permits (or the application of a carbon tax) to compensate households via lump-sum payments can result in an overall reduction in the level of inequality in society. Conversely, policies that use carbon revenues to lower existing taxes on personal income tend to increase the overall level of inequality in society. Meanwhile, this and other studies have also shown that design issues can bear on the overall economic impact of efforts to mitigate greenhouse gas emissions (see Table 6.6). The most economically efficient policies are generally found to be those where revenues from carbon taxation are used to reduce pre-existing distortionary taxes, with the least efficient policies being those that distribute revenues to households in lump-sum.

As in other areas of economic policy, these results suggest a trade-off between equity and efficiency, with the most efficient policies also being the ones that tend to exacerbate income inequalities. In this section, I examine this trade-off explicitly. To do so, I run

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[21] I calculate the Gini coefficient using the relation: $G = \frac{1-\sum_i f(y_i)(S_{i-1}+S_i)}{S_n}$ where $S_i = \sum_{j=1}^{i} f(y_j)y_j$ and $S_0 = 0$, and where y_i is the income of the ith consumer group and $f(y_i)$ is the proportion of the ith consumer group as a fraction of the total popluation.

a series of model simulations in which an increasing share of the total amount of carbon policy revenues are rebated to consumers in lump sum, on an equal per-household basis. Any revenues that are not recycled to households in lump sum are used to reduce the rate of personal income tax, and overall government revenues are maintained at the benchmark level.

Figure 6.8 shows the results of this experiment. The horizontal axis shows the change in the Gini index as a result of policy application; recall that increases in the index (movements to the right in the figure) correspond to increases in inequality, and vice versa. The vertical axis shows changes in total economic output that result from policy application. At the top-right point of the figure is the point where none of the revenues are rebated to households in lump-sum, and all of the revenue is used to lower the personal income tax (such that the income tax is reduced by 32 percent). This point corresponds to the Tax Shift used throughout the earlier discussion, and is associated with an increase in inequality, but with very small (positive) overall economic impacts. Moving along the points to the southwest in the figure corresponds to increases in the proportion of the carbon policy revenues that are rebated in lump sum to households. Along this line, the overall efficiency of the policy is reduced, but the level of inequality is also reduced. The dashed line shows the point where the policy is neutral from a distributional standpoint: this is where about thirty percent of total revenues from the policy are recycled in lump sum to households, and the remainder are used to cut pre-existing taxes and to balance the government budget.

These results convey the flexibility that the policy maker has in choosing the impact of a carbon policy. A policy maker concerned principally with reducing income inequalities would be advised to distribute permit revenues in lump sum to households; conversely, a policy maker concerned with maximizing economic output (and average incomes) would be better advised to use revenues from the carbon policy to reduce or eliminate other pre-existing taxes. A policy maker interested in trading off between the two concerns might choose a combination of the two approaches. Indeed, as outlined in the discussion, this seems to be the approach taken in Canadian policy proposals. For example, British Columbia's carbon tax revenues are recycled substantially as cuts in pre-existing taxes, but a portion is retained for lump-sum transfers to households, since a not insignificant share of poorer households pay little or no income tax and do not benefit from the tax cuts.

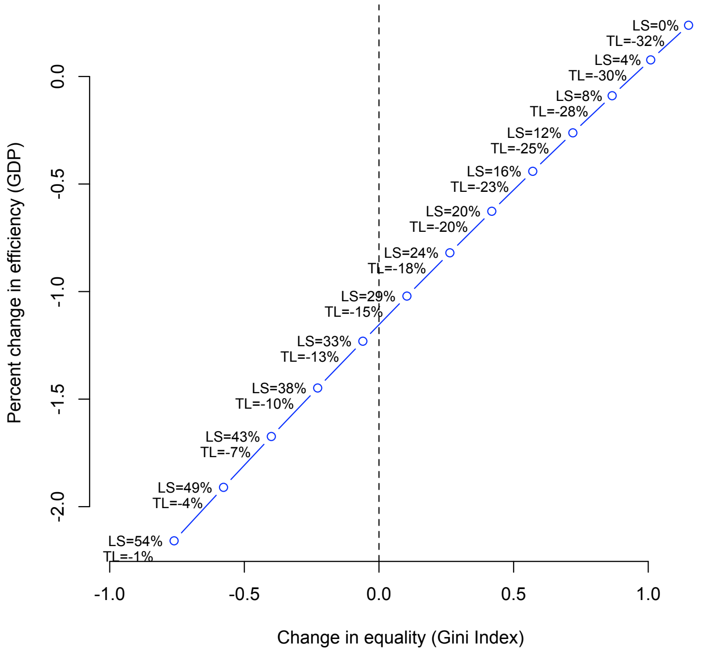

Figure 6.8: Trade off between equity and efficiency

Methodological issues

The main concern of this paper is estimating the impacts of greenhouse gas mitigation policies on individual households. As outlined earlier, these policies can influence individual welfare through several different avenues in the model. First, a carbon policy causes a direct impact on household welfare by increasing the prices of fossil fuels. Households that consume a significant amount of fossil fuels should therefore experience a larger direct loss of consumption than those that consume a small amount. Second, a carbon policy causes an indirect impact on household welfare through its effect on other markets. For example, a carbon price might cause an increase in the price of food, as the agricultural sector passes on some of the costs of the carbon policy to consumers. Effects on other markets can be either positive or negative. For instance, by reducing demand for labour in energy-intensive sectors, a carbon policy can lower wage costs to less energy-intensive firms, and reduce the overall cost of production in these firms. The impact of these second-order effects on household consumption depends on links between markets as well as on the basket of goods consumed by individual households. Third, a carbon policy can impact factor incomes. As producers respond to the carbon policy, they can change the amount of capital and labour they employ, which causes shifts in the overall demand for factors of production, which in turn influences the market-clearing price of these factors. These price changes are transmitted to households in the form of changes in income. Following all of these changes, households can alter their consumption basket, as well as their supply of labour.

As described earlier, most existing literature on distribution impacts of environmental policies uses an input-output approach to estimating household impacts. Such models are able to account for the direct and indirect impacts as described above. However, they do not account for the impact of policies on factor markets. To the degree that households have different endowments of productive factors, and to the degree that elasticities governing labour supply response differ by household, such models will not correctly estimate the distributional impacts of environmental policies. Further, such models do not account for household or firm response to changes in relative prices induced by the policy, and instead assume that actors continue to consume commodities in the same proportions regardless of prices. This assumption could also lead such models to incorreclty estimate distributional impacts. In the model described in this paper, an attempt was made to correctly model both of these aspects of the problem.

To show how the method used in this paper compares to other papers, and to convey the potential errors associated with these other methods, I calculated the distributional incidence of a balanced budget carbon policy, in which revenues raised from carbon pricing are used by government to increase spending, using several different methods:[22]

Direct The direct impact of the policy is calculated as the percentage change in household welfare from increases in fossil fuel prices to final consumers that result from the carbon policy. Households do not respond to the policy by adjusting fossil fuel consumption.

Direct+Indirect The direct plus indirect impact of the policy includes the above impact

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[22] I used a balanced budget analysis here to avoid the need to deal with revenue recycling impacts of policies, which makes the alternative methods more comparable.

plus the impact from changes in the price of other consumer goods measured using an input output approach.[23] Firms are assumed to pass 100 percent of the carbon policy on to consumers as increases in final goods prices. Neither households nor industry responds to the policy by adjusting fossil fuel consumption.

Direct+Indirect+Adjustment This simulation is the same as the above simulation, but allows households to respond to the carbon policy by adjusting consumption of fossil fuels. Industry is still assumed to operate using fixed coefficients.

CGE+Labour market clearing This simulation is run using the computable general equilibrium model. As a result, both households and firms are able to adjust their input mix in response to changes in the prices of fuels. Further, firms do not pass 100 percent of the carbon policy on to consumers as increases in final goods prices, but instead pass some backward onto owners of factors of production, which changes household incomes. In this simulation, the labour market is assumed to clear perfectly, and there is assumed to be a single market for all labour.

CGE+Unemployment+Disaggregated labour This simulation is the same as the above simulation, except that equilibrium unemployment is included in the model as described earlier in the paper. Further, the labour market is disaggregated into 27 distinct occupational categories.

The results are shown in Figure 6.9. The **Direct** effect of the policy amounts to only about one third of the **Direct+Indirect** effect of the policy, suggesting that much of the impact of a carbon policy on consumers is not directly through increases in fossil fuel prices, but indirectly through impacts on prices of other goods. Analysis that focuses uniquely on the consumer side, and ignores pass-through of carbon prices from producers, will underestimate the impact of the policy. There is, however, little difference between the **Direct+Indirect** impact and the **Direct+Indirect+Consumer adjust** scenario, suggesting

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[23] Specifically, I follow Schinnar (1978) and define U, V, q, e, and g as matrices of intermediate inputs, outputs, and vectors of gross commodity output, final demand, and gross industry activity, respectively. Then, letting $\hat{g}$ and $\hat{q}$ be diagonal projections of g and q, and defining $B = U\hat{g}^{-1}$ and $D = V\hat{q}^{-1}$, we arrive at the relation $q = (I - BD)^{-1}e$, where I is the identity matrix, and where the term $(I - BD)^{-1}$ is the matrix of commodity by commodity multipliers. I apply the carbon policy to this matrix to estimate changes in final demand price associated with a carbon policy.

that models that omit consumer behaviour and technology change in response to the carbon policy are unlikely to be severely biased. In contrast, there is a significant difference between the results reported in the **Direct+Indirect+Consumer adjust** scenario and the **CGE+Labour market clearing** scenario. The latter includes the possibility for firms to adjust their input mix in response to changes in prices. While adjustments on the consumer side are small, adjustments on the producer side are much larger, and help to mitigate the impact of the carbon price on households. Further, in this analysis, the carbon price is not passed directly to consumers, but is split between impacting consumers of commodities and owners of factors of production, which spreads more of the impact of the policy onto wealthier households who are disproportionate shareholders of firms and for whom labour is a larger share of total income. Finally, there is a difference between the **CGE+Labour market clearing** and the **CGE+Unemployment+Disaggregate labour** scenario. In particular, allowing for disaggregation of the labour market and unemployment causes the policy to impact more on wealthy households. This occurs because occupations populated by wealthy households have larger reductions in demand in the carbon policy scenario than those populated by poor households. This suggests that properly modeling the labour market can be imporant for capturing the incidence of an environmental (or other) policy.

6.6 Conclusions

This paper had two primary aims, one methodological and one empirical. First, from a methodological standpoint, the paper argues that frequently-used methods for assessing the incidence of environmental policies miss important dynamics. In particular, by assuming that consumers and firms are unable to change input proportions in response to changing prices, existing input-output analyses are likely to overestimate impact of carbon policies on household welfare. The paper showed that assuming no response on the part of households is unlikely to introduce significant errors into the analysis, but that assuming no response on the part of firms is likely to introduce substantial bias. Additionally, by assuming away the possibility that the burden of environmental policies is shifted backward onto factors of production, such methods can produce incomplete and potentially misleading estimates of the total incidence of an environmental policy. In particular, because wealthy households are disproportionate owners of factors of production, input-output methods are

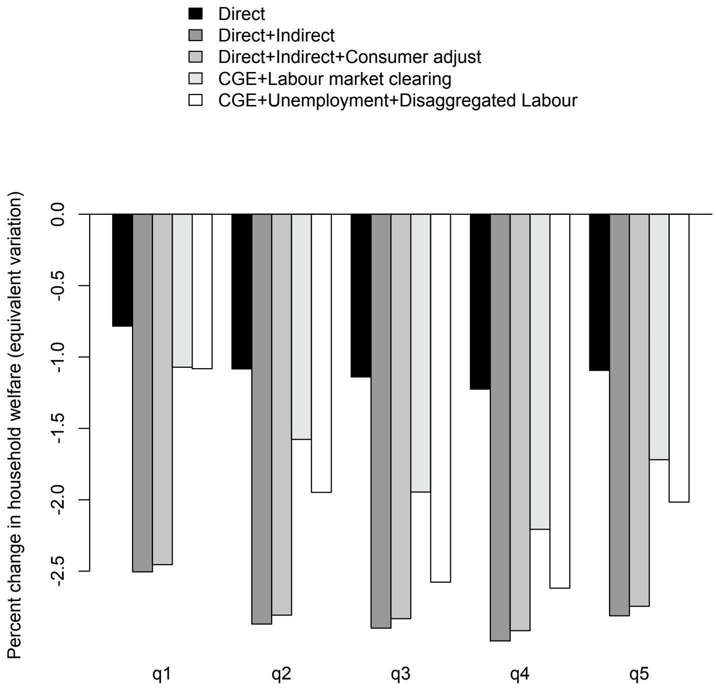

Figure 6.9: Comparison of methods for assessing the distributional impacts of climate change policy

likely to suggest that policies are more regressive than they actually are. Finally, the paper showed that introducing more realism into the labour market - in particular by representing occupational classes in detail and by allowing for equilibrium unemployment - can impact findings on the distributional incidence of climate policy.

Second, the paper aimed to assess the distributional impacts of several alternative policy designs that each aim to reduce carbon dioxide emissions in Canada by 25 percent from business as usual levels over a 10-year period. The analysis suggests that the imposition of a carbon policy on its own is unlikely to be regressive. However, the analysis showed that using revenue from a carbon policy to reduce the existing personal income tax would be regressive, increasing the level of inequality in society by about one point on the Gini index. This type of revenue-recycling policy is often promoted by economists on efficiency grounds. The analysis in this paper confirmed the efficiency argument, showing that using carbon policy revenues to cut pre-existing personal income taxes could offset most of the aggregate negative impacts of the carbon policy.

An alternative use of carbon policy revenues would be to distribute them in lump sum to households. The analysis here suggests that using proceeds from a carbon policy to rebate to households in lump sum would be a highly progressive policy, increasing the level of equality in society by almost one point in the Gini index. However, like other papers, this one finds that there are efficiency costs to this approach - overall economic output is lower in this scenario as opposed to when personal income taxes are cut because an opportunity was missed to reduce distortinary taxation in the economy.

The analysis of various revenue-recycling scenarios suggests that policy makers have substantial control over the distributional impact of a carbon policy. In particular, it appears that there are enough revenues available from a carbon policy for policy makers to effectively choose a desired incidence. Such a choice, however, is likely to have a consequence for overall economic efficiency. To formally explore the tradeoff between equality and efficiency, the paper analyzed a range of scenarios where varying amounts of carbon policy revenue were used to reduce personal income taxes and as lump sum transfers to households. The analysis suggested that using roughly 30 percent of total revenues for lump sum transfers to households, and the remainder to cut labour income taxes, would create no net redistribution of income in society, a potentially desirable goal for policy makers.

6.7 Appendix A: Full algebraic model listing

6.7.1 Full algebraic model

The model is formulated using cost functions that are dual to the production functions described above. Equilibrium is characterized by a full set of zero-profit, market-clearance, and budget balance conditions. The system is solved as a mixed complementarity problem, which allows markets and sectors to be inactive if prices are zero or profits are negative, respectively Rutherford (1995).

Notation

Tables 6.7, 6.8, 6.9, and 6.10 describe the notation used in the model. The overbar notation signifies an exogenous activity level. Capital roman letters are used for activity levels (which are endogenous except when the overbar is present). Lower case roman letters are used for prices (which are endogenous) and for tax rates (which can be either endogenous or exogenous). Lower case greek letters are exogenous parameters.

Table 6.7: Sets

Set	Description
j	Sectors
i	Commodities
q	Markets (producer (P), government (G), consumer (C), investment (I), export(E))
h	Households
l	Occupational categories

Zero profit conditions

1. Production from new-vintage capital (Y_j)

$$\Pi_j^Y = \left(\sum_i py_i^{\theta_i^{Y_j}}\right)^{\frac{1}{1-\sigma}} - c_j^Y\left(w_l(1+t_j^P), r(1+t_j^P), \hat{pa}_i^P\right) \leq 0 \tag{6.15}$$

2. Production from extant capital (X_j)

$$\Pi_j^X = \left(\sum_i py_i^{\theta_i^{Y_j}}\right)^{\frac{1}{1-\sigma}} - c_j^X\left(w_l(1+t_j^P), rx_j(1+t_j^P), \hat{pa}_i^P\right) \leq 0 \tag{6.16}$$

3. Margins ($R_{i,q}$)

$$\Pi_i^{R,q} = \hat{pa}_i^q - pa_i(1+t_i^q) - \sum_m \theta_m^{i,q} pa_m \leq 0 \tag{6.17}$$

4. Armington (A_i)

$$\Pi_i^A = pa_i - \left(\theta_i^A pm_i^{1-\sigma_i^A} + (1-\theta_i^A) pd_i^{1-\sigma_i^A}\right)^{\frac{1}{1-\sigma_i^A}} - cc_i pz \leq 0 \tag{6.18}$$

5. Consumption (C_h)

$$\Pi_h^C = pc_h - c_h^C(\hat{pa}_i^C) \leq 0 \tag{6.19}$$

6. Investment (I)

$$\Pi^I = pi - \sum_i (\hat{pa}_i^I)^{\theta_i^I} \leq 0 \tag{6.20}$$

7. Government (G)

$$\Pi^G = pg - \textstyle\sum_i (\hat{pa}_i^G)^{\theta_i^G} \leq 0 \tag{6.21}$$

8. Welfare (W_h)

$$\Pi_h^W = pw_h - \left(\theta_h^W pc_h^{1-\sigma_h^W} + (1-\theta_h^W)\left(\frac{w_l}{1+\tau_h^L}\right)^{1-\sigma_h^W}\right)^{\frac{1}{1-\sigma_h^W}} \leq 0 \tag{6.22}$$

9. Exports (E_i)

$$\Pi_i^E = pfx - \hat{px}_i \leq 0 \tag{6.23}$$

10. Imports (M_i)

$$\Pi_i^M = pm_i - pfx \leq 0 \tag{6.24}$$

11. Domestic-export transformation (J_i)

$$\Pi_i^J = \left(\theta_i^{T_i} px_i^{1-\sigma_i^T} + (1-\theta_i^T) pd_i^{1-\sigma_i^T}\right)^{\frac{1}{1-\sigma_i^T}} - py_i \leq 0 \tag{6.25}$$

Market clearance conditions

1. Labour market equilibrium (w_l)

$$\sum_h \bar{L}_{l,h} \geq \left[\sum_j Y_j\left(-\frac{\partial \Pi_j^Y}{\partial w_l}\right) + \sum_j X_j\left(-\frac{\partial \Pi_j^X}{\partial w_l}\right)\right]\frac{1}{1-U_l} + \sum_h W_h\left(-\frac{\partial \Pi_h^W}{\partial w_l}\right) \tag{6.26}$$

2. Market equilibrium for malleable capital (r)

$$\sum_h \bar{K}_h \geq \sum_j Y_j \left(-\frac{\partial \Pi_j^Y}{\partial r} \right) \tag{6.27}$$

3. Market equilibrium for extant capital (rx_j)

$$\sum_h \bar{K}\bar{X}_{h,j} \geq \sum_j X_j \left(-\frac{\partial \Pi_j^X}{\partial rx_j} \right) \tag{6.28}$$

4. Market equilibrium for domestic output (py_i)

$$\sum_j Y_j \left(-\frac{\partial \Pi_j^Y}{\partial py_i} \right) + \sum_j X_j \left(-\frac{\partial \Pi_j^X}{\partial py_i} \right) \geq T_i \left(-\frac{\partial \Pi_i^T}{\partial py_i} \right) \tag{6.29}$$

5. Market equilibrium for domestic output used for domestic consumption (pd_i)

$$J_i \left(-\frac{\partial \Pi_i^J}{\partial pd_i} \right) \geq A_i \left(-\frac{\partial \Pi_i^A}{\partial pd_i} \right) \tag{6.30}$$

6. Market equilibrium for domestic consumption before margins (pa_i)

$$A_i \left(-\frac{\partial \Pi_i^A}{\partial pa_i} \right) \geq \sum_q R_{i,q} \left(-\frac{\partial \Pi_i^{R,q}}{\partial pa_i} \right) \tag{6.31}$$

7. Market equilibrium for intermediate inputs to production ($\hat{pa}_i^P$)

$$R_{i,P} \left(-\frac{\partial \Pi_i^{R,P}}{\partial \hat{pa}_i^P} \right) \geq \sum_j \left[Y_j \left(-\frac{\partial \Pi_j^Y}{\partial \hat{pa}_i^P} \right) + X_j \left(-\frac{\partial \Pi_j^X}{\partial \hat{pa}_i^P} \right) \right] \tag{6.32}$$

8. Market equilibrium for exports before margins (px_i)

$$J_i \left(-\frac{\partial \Pi_i^J}{\partial pe_i} \right) \geq R_{i,E} \left(-\frac{\partial \Pi_i^{R,E}}{\partial pE_i} \right) \tag{6.33}$$

9. Exports after margins ($\hat{px}_i$)

$$R_{i,E} \left(-\frac{\partial \Pi_i^{R,E}}{\partial \hat{pe}_i} \right) \geq E_i \left(-\frac{\partial \Pi_i^E}{\partial \hat{pe}_i} \right) \tag{6.34}$$

10. Foreign exchange (pfx)

$$\sum_i E_i \left(-\frac{\partial \Pi_i^E}{\partial pfx}\right) \geq \sum_i M_i \left(-\frac{\partial \Pi_i^M}{\partial pfx}\right) + \bar{B} \tag{6.35}$$

11. Imports (pm_i)

$$M_i \left(\frac{\partial \Pi_i^M}{\partial pm_i}\right) \geq A_i \left(-\frac{\partial \Pi_i^A}{\partial pm_i}\right) \tag{6.36}$$

12. Consumption for investment ($\hat{pa}_i^I$)

$$R_{i,I} \left(\frac{\partial \Pi_i^{R,I}}{\partial \hat{pa}_i^I}\right) \geq \bar{I} \left(-\frac{\partial \Pi^I}{\partial \hat{pa}_i^I}\right) \tag{6.37}$$

13. Consumption for government ($\hat{pa}_i^G$)

$$R_{i,G} \left(\frac{\partial \Pi_i^{R,G}}{\partial \hat{pa}_i^G}\right) \geq \bar{G} \left(-\frac{\partial \Pi^G}{\partial \hat{pa}_i^G}\right) \tag{6.38}$$

14. Private consumption ($\hat{pa}_i^C$)

$$R_{i,C} \left(\frac{\partial \Pi_i^{R,C}}{\partial \hat{pa}_i^C}\right) \geq \sum_h C_h \left(-\frac{\partial \Pi_h^C}{\partial \hat{pa}_i^C}\right) \tag{6.39}$$

15. Aggregate private consumption (pc_h)

$$C_h \left(\frac{\partial \Pi_h^C}{\partial pc_h}\right) \geq W_h \left(-\frac{\partial \Pi_h^W}{\partial pc_h}\right) \tag{6.40}$$

16. Carbon market (pz)

$$\bar{Z} \geq \sum_i A_i \left(-\frac{\partial \Pi_i^A}{\partial pz}\right) \tag{6.41}$$

Budget balance

17. Household budget balance (RA_h)

$$\begin{aligned} RA_h pw_h &= \sum_j \frac{rx_j}{1+t^K}\bar{D}_{j,h}\gamma + \frac{r}{1+t^K}\sum_j \bar{D}_{j,h}(1-\gamma) \\ &+ \sum_l \frac{w_l}{1+t^L_h}\left(\bar{H}_{l,h} - W_h\left(-\frac{\partial \Pi^W_h}{\partial w_l}\right)\right)(1-U_l) \\ &- ps\bar{S}_h + \sum_j \frac{pnr_j}{1+t^N_j}\bar{N}_j(1-\omega) + pc_h\bar{T}_h + pc_h\bar{Q}_h \end{aligned}$$

18. Government consumption (RG)

$$RGpg = V + pz\bar{Z} - \bar{T}pg \tag{6.42}$$

19. Taxes (V)

$$\begin{aligned} V &= \sum_h \left[\sum_l \frac{w_l(\bar{L}_{l,h} - W_h \frac{\partial \Pi^W_h}{\partial w_l})}{(1+t^L)}(1-U_l)t^L\right] \\ &+ \sum_h \left[\sum_j \frac{rx_j\gamma(\bar{P}_j + \bar{F}_j + \sum_h \bar{D}_{j,h})}{(1+t^K)}t^K + \sum_j \frac{r(1-\gamma)\sum_j(\bar{P}_j + \bar{F}_j + \sum_h \bar{D}_{j,h})}{(1+t^K)}t^K\right] \\ &+ \sum_j \left[\frac{pnr_j}{1+t^N_j}t^N_j\bar{N}_j\right] \\ &+ \sum_j \left[\sum_l Y_j \frac{\partial \Pi^Y_j}{\partial w_l}w_l t^P + \sum_k Y_j \frac{\partial \Pi^Y_j}{\partial r_k}r_k t^P\right] \\ &+ \sum_q \left[\sum_i R_{i,q}\frac{\partial \Pi^{R,q}_i}{\partial pa_i}pa_i t^q_i\right] \end{aligned}$$

20. Firm saving (retained profits)

$$psS_F = \sum_j rx_j\gamma\bar{F}_j + r(1-\gamma)\sum_j \bar{F}_j \tag{6.43}$$

21. Pensions

$$psS_P = \sum_j \frac{pnr_j}{1+t^N_j}\bar{N}_j\omega + \sum_j rx_j\gamma\bar{P}_j + r(1-\gamma)\sum_j \bar{P}_j - \sum_h \bar{Q}_h pc_h \tag{6.44}$$

22. Savings-investment

$$piI = psS_F + psS_P + ps\sum_h \bar{S}_h + ps\bar{S}_G + pfx\bar{B} + \sum_i v_i pa_i \tag{6.45}$$

6.7.2 Additional constraints

23. Wage premium associated with unemployment (U)

$$w_l = \left(\frac{U_l}{U_l^0}\right)^{\varepsilon_U} w_l^0 \tag{6.46}$$

6.7.3 Production and function

Based on the nesting structure adopted, it is possible to define a unit cost function associated with sector production:

$$c_j^Y = \left((1-\theta_{vae}^Y)\left(\sum_i \theta_{m_i}\hat{pa}_i^P\right)^{1-\sigma_1^Y} + \theta_{vae}^Y p_{vae}^{1-\sigma_1^Y}\right)^{\frac{1}{1-\sigma_1^Y}} \tag{6.47}$$

where:

$$p_{vae} = \left(\theta_{va}^Y p_{va}^{1-\sigma_2^Y} + (1-\theta_{va}^Y)p_e^{1-\sigma_2^Y}\right)^{\frac{1}{1-\sigma_2^Y}} \tag{6.48}$$

$$p_{va} = \left(\theta_l^Y\left(\sum_j \theta_j^Y pw_j\right)^{1-\sigma_3^Y} + (1-\theta_l^Y)p_k^{1-\sigma_3^Y}\right)^{\frac{1}{1-\sigma_3^Y}} \tag{6.49}$$

$$p_e = \left(\theta_e^Y(\hat{pa}_{ele}^P)^{1-\sigma_4^Y} + (1-\theta_e^Y)p_{fuel}^{1-\sigma_4^Y}\right)^{\frac{1}{1-\sigma_4^Y}} \tag{6.50}$$

$$\tag{6.51}$$

and where:

$$\begin{aligned} p_{fuel} = \Bigg(& (1-\theta_{lqd}^Y)(\hat{pa}_{col}^P)^{1-\sigma_5^Y} \\ & +\theta_{lqd}^Y\left((1-\theta_{rpp})(\hat{pa}_{ng}^P)^{1-\sigma_6^Y} + \theta_{rpp}(\hat{pa}_{rpp}^P)^{1-\sigma_6^Y}\right)^{\frac{1-\sigma_5^Y}{1-\sigma_6^Y}}\Bigg)^{\frac{1}{1-\sigma_5^Y}} \end{aligned} \tag{6.52}$$

Table 6.8: Activity levels

Variable	Description
Y_j	Production from new capital in sector j
X_j	Production from extant capital in sector j
$R_{i,q}$	Margin for commodity i destined for market q
A_i	Armington commodity i
C_h	Consumption for household h
I	Investment
S_F, S_P, S_h, S_G	Savings by firms, pensions, households, and government
$\bar{D}_{j,h}$	Investment income to household h from sector j
G	Level of government provision of public goods
W_h	Welfare level for household h
$\bar{H}_{l,h}$	Household h's endowment of time in occupational category l
RA_h	Income for representative household
RG	Income for government agent
E_i	Level of exports of commodity i
M_i	Level of imports of commodity i
J_i	Level of production of commodity i
$\bar{T}_h$	Transfer from government to household h
$\bar{B}$	Balance of trade surplus
$\bar{F}_j$	Profits retained by firms in sector j
$\bar{N}_j$	Gross natural resource rents in sector j
$\bar{P}_j$	Pension investment income from sector j
$\bar{Q}_h$	Pension payments to household h

Table 6.9: Prices and taxes

Variable	Description
w_l	Gross (before tax) wage rate for employment category l
r	Gross (before tax) capital rental rate for new capital
rx_j	Gross (before tax) capital rental rate for extant capital in sector j
py_i	Price of domestic ouput of commodity i
pd_i	Price of domestic output of commodity i for domestic consumption
pa_i	Price of Armington good i before margins
$\hat{pa}_i^q$	Price of Armington good i destined for market q
px_i	Price of export of commodity i before margins
$\hat{px}_i$	Price of export of commodty i after margins
pfx	Price of foreign exchange
pm_i	Price of imports of commodity i
pi	Price of aggregate investment good
pc_h	Price of aggregate consumption good for household h
pz	Price of carbon permits
t_j^P	Tax on production in sector j
t_i^q	Tax on product i destined for market q
t_h^L	Direct tax on labour income in household h
t^K	Direct tax on corporate income
t_j^N	Natural resource taxes and royalties

Table 6.10: Model parameters

Parameter	Description
$\theta_i^{Y_j}$	Value share of commodity i in total output of sector j
θ_i^T	Value share of exports in domestic production
θ_i^I	Value share of commodity i in aggregate investment
θ_i^G	Value share of commodity i in aggregate government consumption
$\theta_m^{i,q}$	Quantity of margin m associated with bringing one unit of commodity i to market m
θ_i^A	Value share of imports in domestic consumption of commodity i
θ_h^W	Value share of consumption in welfare for household h
σ_i^A	Armington elasticity for commodity i
σ_i^T	Elasticity of substitution between exports and domestic consumption for commodity i
σ_h^W	Elasticity of substitution between consumption and leisure for household h
cc_i	Carbon coefficient for commodity i
γ	Proportion of extant capital in total capital
ω	Proportion of natural resource wealth owned by pensions

Chapter 7

Electric utility demand side management in Canada[*]

7.1 Introduction

Electric utility demand side management (DSM) programs were conceived following the dramatic energy price increases of the 1970s and early 1980s. Increases in fuel prices during this period were accompanied by high interest rates that significantly increased the cost of building and operating new power plants (Gellings, 1996). Responding to the increase in energy prices, the US government implemented a wave of new policies aimed at stimulating energy efficiency, including *The Energy Policy and Conservation Act (1975)*, *The Energy Conservation and Production Act (1976)*, *The National Energy Conservation Policy Act (1978)*, and *The Public Utilities Regulatory Policy Act (1978)* (Gillingham et al., 2006). Electric utility regulators, especially in the US, were also concerned with rising energy prices and with potential misinvestment risks of large-scale generation, and so were persuaded that utilities should be required to foster improved efficiency as well as load shifting by their customers. (By reducing peak demand, load shifting delays the need for new power plants.) Pushed by these interrelated drivers, electric utilities in the US initiated DSM programs that initially focused on load shifting and then increasingly on electric end-use efficiency. Although load shifting programs remain important today, most of the

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DSM focus throughout North America in the past two decades has been on end-use energy efficiency.

In Canada, DSM developed more slowly (Jaccard, 1993). First, the electricity industry, being especially based on hydropower and coal, did not experience the financial crisis of its US counterpart, although Ontario Hydro was caught with significant cost overruns in its nuclear investments. Second, most of the electricity industry was (and still is) publicly owned with little oversight by utility regulatory agencies, so there was no external force to require consideration of energy efficiency. Third, authority over the electricity system is more decentralized in Canada than in the US, so there is no equivalent federal act in Canada to those in the US prompting energy efficiency investments. The development of DSM in Canada therefore depended to a significant degree on personalities and political preferences. In 1986, the CEO of BC Hydro took a personal interest in DSM and launched Power Smart, a division that eventually had influence across the country. Similar developments in Ontario and eventually Quebec led to a patchwork of DSM efforts across the country.

The first utility DSM programs were implemented in California and the US northwest, and have since spread throughout the United States and Canada (Nadel and Geller, 1996). Most large electric distribution utilities in these two countries now have some experience with such programs. Total electric utility spending on DSM in the US between 1990 and 2005 was $36 billion (US$2005), while total spending in Canada over the same period was about $2.9 billion (CAD$2005) (see Figure 7.1 for sources). Once the relative size of the two countries is accounted for, expenditures are relatively similar, although the US out-spent Canada somewhat: Canada spent about $6.01 (CAD$2005) per person per year on DSM between 1990 and 2005, compared to $9.21 (US$2005) in the US. The most aggressive utilities in both countries spend up to 4 percent of their total revenue on DSM, with most utilities spending less than 1.5 percent of total revenue.

As shown in Figure 7.1, spending on DSM in both the US and Canada peaked in 1993, with US utilities spending about $3.7 billion (US$2005) and Canadian utilities spending about $550 million (CAD$2005). As electricity market restructuring efforts intensified throughout much of the US in the mid-1990s, spending on DSM by utilities fell significantly (Nadel and Geller, 1996). Despite the more tentative nature of electricity restructuring in Canada, spending fell even more precipitously than in the US during the latter half of the 1990s. This is particularly as a result of the cessation of all DSM programs by Ontario Hydro (formerly the largest-spending entity in Canada) in the mid-1990s, as government prepared it for restructuring. However, in both countries, DSM programs have enjoyed a resurgence during the last few years. The recent increase has been prompted in part by the volatility and high prices in international energy markets, but also by new concerns about energy-related greenhouse gas emissions. Based on recent utility resource plans, it is likely that DSM spending in Canada in the next few years will surpass the previous high set in 1993.

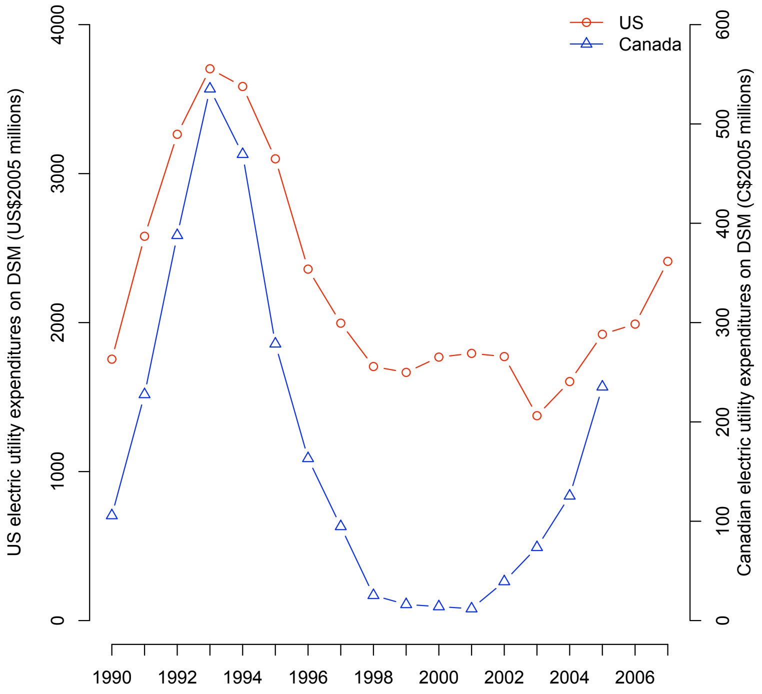

Figure 7.1: Electric utility demand side management expenditures in US and Canada, 1990-2005. US data from US Energy Information Administration *Electric Power Annual*. Canadian data was collected for this study from the sources described herein.

Despite the substantial investment in DSM over the past two decades, the impact of the spending is not possible to discern directly and remains the subject of significant controversy, both in academic literature and in utility regulatory processes. Unlike supply side investments in new generation capacity, DSM investments do not result in tangible, utility-owned assets whose output can be measured directly. Instead, electric utilities must infer the results of DSM programs through program evaluations that seek to estimate the incremental (or additional) effect of DSM programs on the underlying natural evolution of energy or electricity efficiency in a given economy. While these have improved over the last two decades, effective evaluation of DSM programs remains a difficult and contentious exercise.

This paper aims to estimate the degree to which utility DSM programs have reduced electricity consumption in Canada over the past two decades using a method significantly different than that used by utilities. Following the example of some studies of the US, we use the significant inter-temporal variation in DSM effort by the utilities in Canada as a quasi-experiment to econometrically infer the effectiveness of these programs. Unlike previous studies, we estimate a partial-adjustment dynamic model of electricity demand, from which both short-run and long-run responses of the economy to DSM expenditure can be predicted. While this method is associated with its own set of challenges, it avoids some of the weaknesses of more common forms of program-focused DSM evaluations.

This type of study can contribute to two related public policy debates. First, because utility DSM spending, by both electricity and natural gas utilities, is projected to increase rapidly in Canada during the coming years, it is important to have an understanding of the potential reduction in energy demand that results from such spending, and the cost of energy efficiency relative to new investments in electricity and natural gas supply. By using a method that is not normally employed by utilities, this study can provide a confirming or contrasting estimate about the degree to which DSM programs can reduce energy demand in a given region.

Second, and perhaps more importantly, this study can provide an indication of the likely effectiveness of any subsidy program aimed at inducing energy efficiency. With increasing concerns about climate change, subsidy programs for energy efficiency are increasing in scope and magnitude. These may be government subsidy programs, utility DSM subsidy programs or even the increasingly popular carbon offsets programs, in which individuals or firms voluntarily pay offset companies to subsidize actions by third parties that apparently reduce GHG emissions from what they otherwise would be. Energy efficiency is frequently a target of these voluntary subsidies. Since there is little in the way of formal ex poste analysis by governments or independent agencies to measure the effectiveness of these subsidies in inducing energy efficiency and thus reducing GHG emissions, this evaluation can provide an independent indication of their likely effectiveness, with important implications for the choice of policy instrument for achieving provincial, national and global GHG reduction targets.

The remainder of the paper is structured as follows. In section 2, we summarize estimates made by utilities relating to the effectiveness of DSM programs, and also describe the challenges associated with such evaluations. In section 3, we describe academic studies that have sought to estimate the effectiveness of US DSM programs. In sections 4 and 5, we outline the method and data that are used in this study to assess the effectiveness of Canadian DSM programs. In section 6, we present the results of the model, and in section 7, we conclude.

7.2 Electric utility assessment of DSM effectiveness

Most utilities that invest significantly in DSM also invest in measurement and verification programs to determine the effectiveness and cost-effectiveness of such spending. Eto et al. (1995), in a survey of commercial sector DSM programs in the US, report that the mean utility-estimated cost for conservation through DSM programs is \$0.027/kWh. This is similar to recent estimates in Canada. For example, Manitoba Hydro, in its 2006 DSM plan, estimated a utility cost of \$0.019/kWh of avoided demand. BC Hydro, in its 2006 Integrated Electricity Plan, reported costs of \$0.032-0.076/kWh. Similarly, the Ontario Power Authority estimated a levelized cost of \$0.020/kWh for DSM programs offered by local distribution companies in 2006. In nearly all cases, estimates made by utilities suggest that reducing electricity demand through DSM expenditures is significantly less expensive than investing in new generation.

Utilities use a variety of techniques to estimate the effectiveness and cost-effectiveness of DSM programs, both prior to program implementation and also after the program has been running. While these techniques can be quite sophisticated, and benefit from the detailed micro-data on electricity sales available to the utility, such program level evaluations must make difficult judgements about important factors that are key to program effectiveness: the free ridership rate, the spillover rate, and the rebound effect. Unfortunately, there is no widely accepted method for estimating these factors.

7.2.1 Free riders

DSM programs are generally targeted at providing incentives for consumers or businesses to adopt more energy efficient equipment. However, adoption of energy efficient equipment also occurs in the absence of DSM programs, as old technologies become obsolete and are replaced with newer and more energy efficient technologies. For example, Natural Resources Canada (2006b) estimates that houses built in 2002 are about 35 percent more energy efficient than similar houses built in the 1970s, and that new models of many major household appliances were almost twice as efficient in 2002 compared to 1990. These changes in efficiency can be the result of (1) an evolution toward stricter government efficiency regulations in buildings and equipment, (2) utility and government DSM programs, (3) increases in energy prices and energy price expectations, and (4) natural gains in energy productivity (as well as labour and materials productivity) that occur as firms and households adopt newer technologies. Energy analysts refer to this latter phenomenon, which existed in decades prior to the 1970s as well, as autonomous energy efficiency improvement.

Given this mix of potential causal factors for improvements in energy efficiency, the main challenge is to estimate how much adoption of energy efficient technologies would have occurred without the DSM program, and thus how much can be attributable to the program (Horowitz, 2004). There is an important temporal dimension to this challenge: given the general trend towards improved efficiency of technologies, part of the effect of a DSM program is likely to shift the timing of investments, rather than the overall magnitude. When a DSM program is applied, it cannot normally distinguish between individuals who would have adopted the energy efficient technology anyway, called free riders, and those who required the DSM subsidy to do so (Loughran and Kulick, 2004). Free riders add to the utility cost of a subsidy program without contributing to its effectiveness. Formally, this is an adverse selection problem, created by differences in information between the electric utility and its customers. However, the utility evaluation literature refers to the issue as a free-ridership problem, and we follow this nomenclature here.

Although accounting for free riders was less common when DSM programs were first introduced, most large utilities now attempt to account for them, typically by conducting follow up surveys of program participants asking whether they would have adopted a particular energy efficiency measure in the absence of the DSM program. Those participants who indicate they would have adopted the technology even in the absence of the subsidy are considered free riders. As an alternative, some utilities calculate free riders on a given program by comparison with a group of non-participants, either within the region or in a different region. The percent of non-participants that adopts the energy efficiency measure is considered to be the free rider percentage.

Calculations by utilities using these methods often show fairly low free ridership levels. For example, a survey of the 40 largest commercial sector DSM programs in the US by Eto et al. (1995) found an average free ridership rate reported by utilities of 12.2 percent. In a non-representative survey of DSM evaluations in Canada, we found a utility-reported average free-rider rate of 14 percent for 11 commercial and residential sector programs.

However, both of these methods have drawbacks, which result in uncertainty and potential bias in free ridership estimates. In particular, stated preference data can be biased because when answering a survey, consumers do not face real world constraints (e.g., time, budget, or information constraints). Errors or bias may arise if consumers do not understand the survey properly, have difficulty recalling historical decisions, or if they purposefully bias their answers to alter the survey results (Louviere et al., 2000).

Estimating free ridership can equally be a challenge when comparing efficiency adoption associated with the DSM program with efficiency adoption by a control group within or outside the region with the program. Non-participants within a region are by definition those customers who are less likely to undertake conservation activities than program participants, and are therefore an inappropriate control group (Hartman, 1988). Non-participants outside of the region may not be comparable with participants within the region for reasons that are both observable (income, house size, etc.) as well as unobservable (attitudes towards conservation, willingness to adopt new technologies, etc.). While an inter-region comparison can account for observable differences, it cannot usually account for unobservable differences in the cross-sectional approach that is used in most program evaluations. To the extent that these are important in explaining technology adoption, inferences made from such comparisons will yield incorrect estimates of free ridership.

The academic literature contains a variety of techniques that attempt to determine the number of free riders on a DSM subsidy program in a way that avoids the issues discussed above. For example, Malm (1996) used a cluster analysis to allocate households from the US Residential Energy Consumption Survey into groups of similar households. With these groups in place, he examined heating system efficiency choice contingent upon the presence and magnitude of DSM programs. This technique aims to correct for some unobserved drivers of energy efficient technology adoption that could be similar between clusters, and results in a free ridership estimate of 89 percent for heating system programs. Train and Atherton (1995) used combined market and survey data in a discrete choice model to find free ridership rates of 36 percent for refrigerator programs and 66 percent for air conditioner programs. Grösche and Vance (2009) use a similar technique and estimate a free ridership rate of about 50 percent for a recent German retrofit program. Loughran and Kulick (2004) estimated a panel model relating electricity sales at all major US electric utilities to spending on DSM programs. The results of this model suggest that DSM expenditures are much less cost effective than claimed by utilities, indicating overall free ridership rates (an average of all utility DSM programs in all sectors) on the order of 50-90 percent.

In general, the free ridership rate calculated by utilities is usually significantly lower than that calculated in independent academic research. By implication, the DSM energy savings estimates of utilities will be higher and their estimated cost of DSM lower.

7.2.2 Spillover

While free riders can erode the impact of a DSM program, spillover does the opposite. Spillover occurs if a DSM program induces energy efficiency improvements in addition to those directly caused by the program. For example, a participant in an energy efficient lighting program, impressed with energy savings from efficient lighting in a given facility, might decide to install efficient lighting in other facilities. Additionally, a DSM measure could induce non-participants to improve efficiency, for example by changing the market for a given technology. In BC Hydro's 2002-2005 seasonal LED program, the utility estimates that virtually all seasonal LEDs sold in the province were indirectly a result of the utility's efforts, so that although coupons for LEDs were estimated to reduce demand by only 0.861 GWh, the overall impact of the program was estimated to be 13.9 GWh (Sampson

Research, 2005). Such impacts are referred to as participant spillover and non-participant spillover respectively, and improve the effectiveness of the program without adding to its costs. Non-participant spillover is not limited to spillover within a jurisdiction. For instance, BC Hydro's evaluation of its seasonal LED program attributes increased penetration of seasonal LEDs throughout Canada to the program (Sampson Research, 2005).[1]

Estimation of spillover rates by electric utilities usually follows the same general techniques as estimation of free ridership rates. In this case, both participants and non-participants are surveyed with hypothetical questions about technology adoption with and without the DSM program. As with free ridership estimates, such questions can result in poor estimates of true spillover rates if respondents have difficulty with purchase recollection or are uncomfortable with the hypothetical nature of the questions.

Utilities often correct estimates of DSM effectiveness for estimated spillover. However, we are not aware of any academic studies that attempt to estimate spillover rates empirically in a rigorous way. Largely, this is because it is empirically difficult to distinguish between real spillover effects and autonomous market developments that would have occurred without any program in place. Horowitz (2007) comes closest, conducting a comparative study of energy efficiency trends in each of the US states, and speculating that residential energy efficiency programs in particular have impacts that spread rapidly between states, implying a high spillover rate.

7.2.3 Rebound effect

The potential reduction in energy consumption resulting from adoption of an energy efficiency measure can be eroded as a result of the rebound effect. The rebound effect exists because improving the energy efficiency of a given energy service (while holding real fuel prices constant) reduces the cost of using that energy service, which can increase demand for the service, and therefore erode the net energy savings from the adoption of the energy efficiency measure. With a high enough elasticity of substitution between energy services and other goods, it is theoretically possible that the rebound effect overwhelms energy savings, such that increases in energy efficiency lead to increases in overall energy

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[1] Although the utility claimed these savings were due to its DSM efforts, these savings were not included explicitly in its estimates of savings.

consumption (Saunders, 1992).

Empirical estimates of the direct rebound effect vary significantly between studies, but Greening et al. (2000) and Sorrell (2007) conclude from a review of several hundred empirical studies that the magnitude of the rebound effect is ‘insignificant to moderate’, and that available studies are associated with significant uncertainty. Specifically, for space heating in the residential sector, they report a rebound effect of 10-30 percent (meaning that this percentage of energy savings from adoption of energy efficiency measures is eroded due to the rebound effect), for space cooling 0-50 percent, for lighting, 5-20 percent, and for water heating, 10-40 percent. Results for firms are less conclusive, but suggest a rebound effect less than 30 percent in the short run, and somewhat larger in the long run.

Although the available empirical and theoretical evidence suggests that up to one third of the energy savings due to adoption of energy efficiency measures are eroded due to the rebound effect, utility evaluation protocols often do not include the rebound effect in calculating the effectiveness of DSM programs, in part because of the difficulty of obtaining appropriate estimates at a program level. As a result, it is likely that utility estimates of energy savings overestimate actual energy savings.

Although we will not be able to directly estimate the magnitude of the rebound effect from our data, Sorrell and Dimitropoulos (2007) show that the own price elasticity of energy demand is an upper bound on the direct rebound effect. Specifically, the absolute value of the own price elasticity of energy demand is equal to the direct rebound effect, provided that (among other assumptions) the consumer’s response to increases in energy efficiency is equivalent to reductions in energy price, and that the consumer responds to these changes by altering intensity of equipment use but not equipment efficiency. Since the last of these assumptions is likely to be incorrect, the own price elasticity is likely an overestimate of the direct rebound effect. However, the total rebound effect (including indirect rebound) is likely to be larger than the direct rebound effect for a variety of reasons.

7.3 Aggregate econometric estimates of DSM effectiveness

Because of these factors that complicate program level analyses of DSM, several studies have attempted to develop and estimate empirical models that indirectly account for these difficulties in a way that avoids making restrictive assumptions. Most of these studies use a time-series cross-section (panel) approach, which greatly increases the number of observations available, allows for a more detailed model specification to be tested with greater reliability, helps to address unobserved heterogeneity, and also enables testing of key time-dependent lags. In particular, these studies have estimated parameters for variants of the following relationship:

$$EFF_{it} = DSM_{it}\beta + \boldsymbol{X}'_{it}\boldsymbol{\alpha} + \varepsilon_{it} \tag{7.1}$$

where EFF_{it} is a measure of energy efficiency in region i at time t, DSM_{it} is a measure of DSM effort, possibly lagged by one or more years, $\boldsymbol{X}_{it}$ is a vector of characteristics of the electric utility and customers in the region, ε_{it} is an error term that may be serially correlated and heteroscedastic, and $\boldsymbol{\alpha}$ and β are parameters to be estimated.

Parfomak and Lave (1996) estimated a variant of equation (7.1) in which DSM effort is given by utilities' reported estimates of savings from commercial and industrial DSM programs, and energy efficiency (EFF_{it}) is proxied by utility electricity sales. They collected data from a sample of 39 utilities in the US northeast and California from 1970 to 1993 to estimate the model. This formulation allows them to interpret β as a 'realization rate': essentially the relationship between utility estimates of conservation and the 'true' realized level of conservation. Estimation of the model suggests that the realization rate is very close to 100 percent, with a 95 percent confidence interval of 43 to 156 percent. Provided utility costs for DSM programs are reported accurately, this estimate suggests that utility cost effectiveness estimates should likewise be accurate.

Loughran and Kulick (2004) estimated equation (7.1) using utility-reported expenditures on DSM programs as a measure of effort (DSM_{it}) and electricity sales as a measure of efficiency (EFF_{it}). Their data covers all large electric utilities in the US from 1989 to 1999, and is derived from form EIA-861 - a census of electric utilities which includes DSM expenditures and savings that is annually administered by the Energy Information Administration. With this formulation, β is interpreted as the elasticity of electricity sales with respect to DSM investments (the equation is estimated in log-log form). From this measure, Loughran and Kulick inferred the cost effectiveness of DSM programs, given as the cost of reducing electricity demand by one kilowatt-hour. To account for the fact that DSM investments may influence electricity sales not just in the year of program implementation, but also in future years, they included DSM expenditure as a stock variable and include

DSM expenditures lagged by two years in their effort variable (DSM_{it}), and tested (but did not report) variations of the model with DSM lagged by as much as four years. Using this formulation, they reported point estimates suggesting that DSM programs have cost between \$0.06 and \$0.22/kWh of reduced electricity consumption, significantly higher than most utilities themselves reported during this time period. They concluded that utilities' estimates of ex poste free ridership rates are likely biased downwards.

The Loughran and Kulick study has been controversial, attracting research that counters and supports its findings. Geller and Attali (2005) noted that since the specification estimated by Loughran and Kulick only includes two lags of DSM expenditures, it is likely to underestimate the cost effectiveness of DSM programs, since these are likely to have effects that last longer than 3 years. While Loughran and Kulick discussed model specifications involving as many as four years of lagged DSM expenditures, Geller and Attali claim that even this may be insufficient to fully capture the potentially highly persistent impact of DSM programs. However, this criticism was countered by Gillingham et al. (2006), who suggested that Geller and Attali misunderstood the estimation approach used by Loughran and Kulick. In particular, by treating DSM expenditures as a stock as opposed to a flow in their first differenced model, Loughran and Kulick accounted for the persistence of DSM expenditures, beyond even the two lags explicitly estimated in their model.

Auffhammer et al. (2008) provided two alternative criticisms. First, they suggested that the calculation used by Loughran and Kulick to convert DSM elasticity to DSM cost effectiveness should weight utilities according to size, rather than equally. Correcting for this makes DSM appear more cost effective than in the original Loughran and Kulick study. Second, they implemented a bootstrapping procedure to develop confidence intervals around Loughran and Kulick's point estimates. Since these confidence intervals include the cost effectiveness estimates of utilities, frequently \$0.01-0.03/kWh, Auffhammer, Blumstein, and Fowlie concluded that the results from Loughran and Kulick's study are insufficiently precise to statistically reject utility estimates of DSM effectiveness.

Horowitz (2007) converted DSM energy savings from the EIA-861 database to an ordinal measure of DSM effort at the state level (DSM_{it}) and used state level energy intensity as a measure of energy efficiency (EFF_{it}) to estimate equation (7.1). He found that states with utilities that have a strong commitment to DSM programs have reduced energy intensity much faster than those with a weak commitment to energy efficiency programs. Although this suggests that DSM programs have been effective at reducing energy intensity, it is not possible to infer either a realization rate or a cost effectiveness estimate from this study.

Horowitz (2004) produced another similar study, but focusing on the commercial sector only, and using continuous, rather than ordinal, values as a measure of DSM effort. This study suggests that DSM expenditures from 1989 to 2001 reduced commercial sector electricity intensity by roughly 1.8 percent, suggesting a realization rate of 54 percent. This is relatively similar to the Loughran and Kulick estimate, again suggesting that utilities have overestimated cost effectiveness of DSM programs. Like Loughran and Kulick, however, Horowitz does not provide confidence intervals around the estimate, making it hard to reject utility estimates of cost effectiveness or realization rate.

Most recently, Arimura et al. (2009) have updated the analysis of Lougran and Kulick as well as Auffhammer, Blumstein, and Fowlie. Starting from the same base data set on utility DSM spending (but with a longer time dimension), they include contemporaneous energy efficiency regulations as an additional explanatory variable, and also include state-level spending on energy efficiency programs that falls outside of utility DSM expenditures. Additionally, they estimate the model in non-linear form, allowing for declining marginal effects of DSM expenditures as the level of expenditures increases. They find an average DSM cost effectiveness of about \$0.06/kWh, with a 95 percent confidence interval of about \$0.025-0.11/kWh, and they find that the marginal effectiveness of DSM expenditures decreases with additional expenditures, as predicted by theory.

Overall, these aggregate studies suggest that electric utility DSM programs in the US over the past three decades have been between 50 and 100 percent as effective as utilities themselves have estimated. The cost of such programs per unit of electricity consumption reduced would therefore be between equal to and double what utilities have estimated. However, there is significant uncertainty in these estimates, suggesting the value of additional research. This is particularly the case since virtually all studies to date have used the same data set, derived from EIA's form 861. Given the ongoing nature of this dispute, and its critical importance for future energy efficiency policy, testing of different data sets, model formulations, and jurisdictions may help to clarify some of the key issues.

7.4 The model

This section uses an approach similar to those described in the previous section to estimate the impacts of DSM expenditures on energy consumption. The estimates are based on a data set containing electric utility DSM expenditures and electricity sales in Canada from 1990 to 2005. Since DSM programs were initiated only in the late 1980s in Canada, this period covers nearly the entire Canadian experience with such programs up to 2005.

The impact of utility DSM expenditures on electricity sales can be captured in the following equation:

$$\log kWH^*_{it} = \phi_{it} + DSM_{it}\beta_{it} + \boldsymbol{X}'_{it}\boldsymbol{\alpha}_{it} + \varepsilon_{it} \tag{7.2}$$

Here, kWH^*_{it} is the consumption of electricity per capita in province i in year t, measured in kWh, DSM_{it} is the per capita expenditure on demand side management, $\boldsymbol{X}_{it}$ is a vector of length k of observed characteristics of the utility and the customers it serves, ϕ_{it}, β_{it}, and $\boldsymbol{\alpha}_{it}$ are coefficients, and ε_{it} is an error term.

The '*' on the left hand side variable indicates desired, rather than actual, electricity consumption. Because electricity-using capital generally lasts for several years, and because firms and households cannot immediately adjust electricity consumption in response to changes in electricity price, demand side management incentives, or other variables, actual electricity consumption may deviate from desired electricity consumption. We assume a constant-elasticity adjustment process between actual and desired electricity consumption, such that actual electricity consumption can be modeled as:

$$\frac{kWH_{it}}{kWH_{i,t-1}} = \left(\frac{kWH^*_{it}}{kWH_{i,t-1}}\right)^{\psi_{it}} \tag{7.3}$$

where ψ_{it} is a parameter that can take on values between 0 and 1. A value of 1 indicates that full adjustment to desired energy consumption takes place immediately, and implies that there is no inertia in adjusting energy consumption following an exogenous shock. A value of 0 indicates that no adjustment towards desired energy consumption following a shock is possible. Taking logarithms and substituting (7.2) into (7.3) gives:

$$\log kWH_{it} = \psi_{it}\left(\phi_{it} + DSM_{it}\beta_{it} + \boldsymbol{X}'_{it}\boldsymbol{\alpha}_{it} - \log kWH_{i.t-1}\right) + \log kWH_{i,t-1} + \psi_{it}\varepsilon_{it} \tag{7.4}$$

Letting $\omega_{it} = \psi_{it}\phi_{it}$, $\delta_{it} = \psi_{it}\beta_{it}$, $\boldsymbol{\eta}_{it} = \psi_{it}\boldsymbol{\alpha}_{it}$, $\lambda_{it} = 1 - \psi_{it}$, and $\mu_{it} = \psi_{it}\varepsilon_{it}$, we obtain:

$$\log kWH_{it} = \omega_{it} + DSM_{it}\delta_{it} + \boldsymbol{X}_{it}'\boldsymbol{\eta}_{it} + \log kWH_{i,t-1}\lambda_{it} + \mu_{it} \tag{7.5}$$

Equation (7.5) is a partial adjustment model of electricity demand, of the type commonly used in studies of the electricity sector as well as for other energy commodities (Houthakker et al., 1974). Although it is an *ad hoc* model, not directly derived from consumer theory, it is commonly used because it is parsimonious and specifies an explicit dynamic adjustment process. This allows both short-run and long-run responses to exogenous shocks to be determined. In the current context, it allows us to estimate both short- and long-run responses to demand side management expenditures. Assuming the demand side management variable is measured in levels (rather than logs), a \$1 expenditure on DSM in province i at time t is associated with a δ_{it} percent change in electricity demand in period t.[2] This is the short-run response. In the long-run, the same expenditure is associated with a $\frac{\delta}{1-\lambda}$ percent change in electricity demand.

Estimation of (7.5) in its current form however, is impossible, since the number of coefficients to be estimated exceeds the number of data points. To make estimation possible, some restrictions have to be put on coefficients.

An obvious starting point is to restrict coefficients to be time invariant:

$$\log kWH_{it} = \omega_i + DSM_{it}\delta_i + \boldsymbol{X}_{it}'\boldsymbol{\eta}_i + \log kWH_{i,t-1}\lambda_i + \mu_{it} \tag{7.6}$$

In this formulation, coefficients are allowed to vary across utilities, so for example the effectiveness of DSM expenditures is able to vary from one utility to another. Estimation of (7.6) is possible, provided that 4 + k < T. It is exactly equal to estimation of separate time series models for each of the utilities in the sample. This strategy is attractive because it puts a relatively small number of restrictions on the model coefficients. However, in the current sample, which has a relatively short time dimension (16 years), estimation is unlikely to yield precise coefficient estimates. Much more precision could be gained if it were possible to restrict coefficient values (except for intercepts) to the same value for all utilities, as in the following:

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[2] We measure DSM in levels rather than logs because so that we can include utility-year pairs where DSM expenditures are zero.

$$\log kWH_{it} = \omega_i + DSM_{it}\delta + \boldsymbol{X}'_{it}\boldsymbol{\eta} + \log kWH_{i,t-1}\lambda + \mu_{it} \tag{7.7}$$

We test whether the joint restrictions imposed by (7.7) are warranted by using an F-test.

In (7.7), ω_i captures unobserved time-invariant heterogeneity across utilities. Because it is unobserved, we can include it with the error to form a compound error term $\nu_{it} = \mu_{it} + \omega_i$. Problems can arise in estimation of (7.7) if ν_i is correlated with the other covariates. Two data transformations are generally employed to deal with this issue: differencing and within-group demeaning. We use the former here:[3]

$$\begin{aligned}\log kWH_{it} - \log \overline{kWH}_i = {} & (DSM_{it} - \overline{DSM}_i)\delta + (\boldsymbol{X}'_{it} - \overline{\boldsymbol{X}}'_i)\boldsymbol{\eta} \\ & + (\log kWH_{i,t-1} - \log \overline{kWH}_{i,-1})\lambda + (\mu_{it} - \bar{\mu}_i)\end{aligned} \tag{7.8}$$

In (7.8), the overbar denotes a time-average. Both differencing and demeaning eliminate ω_i and should eliminate this source of bias in model coefficients.

It is possible that the idiosyncratic error term is serially correlated, such that $E(\mu_{it}\mu_{is}) \neq 0 \; \forall \; t \neq s$. We therefore estimate the model using generalized least squares, allowing for a first order autoregressive error structure, in addition to the ordinary least squares approach described above.

The presence of the lagged dependent variable introduces additional complication into the model estimation. As Nickell (1981) shows, in the presence of a lagged dependent variable, the demeaning strategy generates correlation between the lagged variable and the error term, which results in biased coefficients. Several strategies have emerged to deal with this problem, mostly involving instrumenting the lagged dependent variable with additional lags that are truly exogenous (Arellano and Bond, 1991; Blundell and Bond, 1998). However, these general method of moments strategies rely on a large number of cross-sectional observations, and so are inappropriate in the current context where the number of cross sectional units is small and fixed. Instead, Kiviet (1995) derives a ‘correction’ for the bias present in the demeaned model and adjusts coefficient estimates with this correction. Monte Carlo evidence suggests that this correction is appropriate for the dimensions of data in this

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[3] We conduct unit root tests to ensure that the variables of concern are stationary. A Levin-Lin-Chu panel unit root test rejects the null hypothesis of a unit root for the sales variable (p=0.0188) and for the DSM expenditure variable (p=0.0020). Thus we do not transform our variables using differences.

study (Judson and Owen, 1999). As a result, we report coefficient estimates corrected for the bias resulting from the presence of lagged dependent variables.

We include key variables that are expected to influence electricity sales in $\boldsymbol{X}_{it}$, with all variables in log form:

1. the number of heating degree days, measured from an 18^o base
2. the number of cooling degree days, measured from an 18^o base
3. the residential retail electricity price, in dollars per kWh
4. gross provincial product per capita, in 2005 Canadian dollars
5. the price of the closest substitute energy for electricity (natural gas in all but Atlantic provinces; heating oil in Atlantic provinces, where natural gas is unvailable) in dollars per GJ
6. the percentage of total end-use electricity consumption by the residential sector

Finally, we note that the price variables in the model are not strictly exogenous, since the price and quantity of electricity consumption may be co-determined. We tried to find appropriate instruments for the electricity price in the model, including the cost of fossil fuels and capital inputs. However, most electricity in Canada is produced from hydro and nuclear sources, so fossil fuel prices are very poorly correlated with electricity prices, and we could not find an appropriate capital cost series that was adequately disaggregated. Consequently, we use electricity prices directly in the model, with the caveat that inferences on coefficients may overlook the interdependence of electricity price and quantity. We think that this problem is less severe than in other markets, however, because electricity prices throughout Canada are generally regulated, with prices set in the year or years prior to the actual year that consumption takes place. To the degree that regulators are not forward-looking, electricity price can therefore be considered relatively exogenous. Paul et al. (2009) use a similar identifying assumption in their recent study of electricity demand in the US.

A similar problem may exist for the variable of interest - demand side management expenditures. In particular, it is possible that demand side management expenditures are influenced by electricity sales, perhaps because jurisdictions with robust growth in electricity are more likely to implement DSM programs. If this is the case, estimation of the current model will result in biased coefficient estimates. We discuss the implications of such endogeneity further below.

7.5 Data sources

Although Statistics Canada requires regular reporting by utilities on electricity generation capacity, electricity sales and revenues, and other information, it does not make this data public, except as provincial aggregates. Additionally, neither Statistics Canada nor any other federal department maintains data on DSM expenditures or energy savings from these programs. As a result, we conduct our analysis at a provincial level, and like Parfomak and Lave (1996), we gathered our data on DSM effort from individual electric utilities.

We gathered data on electric utility DSM spending between 1990 and 2005 from electricity distribution utilities in each Canadian province.[4] Data were gathered mostly from utility, utility regulator, and government publications and were supplemented with a structured spreadsheet survey and unstructured interviews of electric utility staff. For most utilities, data were not available to show the breakdown of historical DSM spending between sectors or by activity type. Additionally, we were not able to collect data on utility estimates of energy savings from DSM programs, but only on DSM expenditures. Finally, we were not always able to distinguish between DSM spending aimed at load shifting and DSM spending aimed at energy efficiency, but where such disaggregation was available, the majority of expenditures (about 75 percent) were directed towards energy efficiency programs. Thus, we include all demand side management expenditures in our DSM variable. We aggregate the data on DSM spending to a provincial level to match the dimensions of the rest of the data in our set.

Other data are sourced from Statistics Canada and Natural Resources Canada. In particular, the volume of electricity sales is derived from Statistics Canada Table 127-0001, and is given by ‘Total available’ electricity minus ‘Total industrial generation’. Sales are bro-

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[4] In some cases, a province is served by more than on distribution utility. In these cases, we gathered data from each of the utilities individually or from sources that tabulated DSM activity for all utilities in a province (this was the case in Ontario).

ken down by end user based on data from Statistics Canada Tables 128-0002 and 128-0009. Population is from Table 051-0001, gross domestic product is from Table 384-0001, heating and cooling degree days are by request from Natural Resources Canada. Natural gas and heating oil prices are from Tables 129-0003 and 326-0009, respectively, and electricity price is by request from Natural Resources Canada.

In total, our data set forms a balanced panel consisting of 160 observations from 10 provinces over 16 years. A summary of the data is provided in Figure 7.2 and Table 7.1. Several trends are obvious in the data. First, in most provinces, electricity consumption is increasing gradually throughout the 16 year period of observation.[5] However, in most provinces electricity consumption has fallen for at least part of the period under observation. Second, prices in most provinces are very stable over time since utility prices were regulated, suggesting that it will probably be difficult to obtain precise estimates of price elasticity. Third, most utilities have engaged in demand side management spending during the sample period (Alberta was the only province with no DSM spending at all during the period), and there is substantial intertemporal variation in DSM spending in most provinces, suggesting that if DSM has an effect on electricity sales, it should be possible to identify it in the data.

Table 7.1: Summary statistics

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Sales per capita	0.015	0.005	0.006	0.025
DSM expenditure per capita	3.51	5.574	0	33.133
GDP per capita	0.031	0.007	0.019	0.061
Electricity price	9.365	1.87	6.092	14.557
Price of electricity substitute	34.159	15.48	8.539	77.467
Heating degree days	4615	852.29	2627	6773
Cooling degree days	122.706	98.976	10	493
Fraction of sales to residential	0.283	0.076	0.126	0.385

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[5] Although, as discussed earlier, it is stationary.

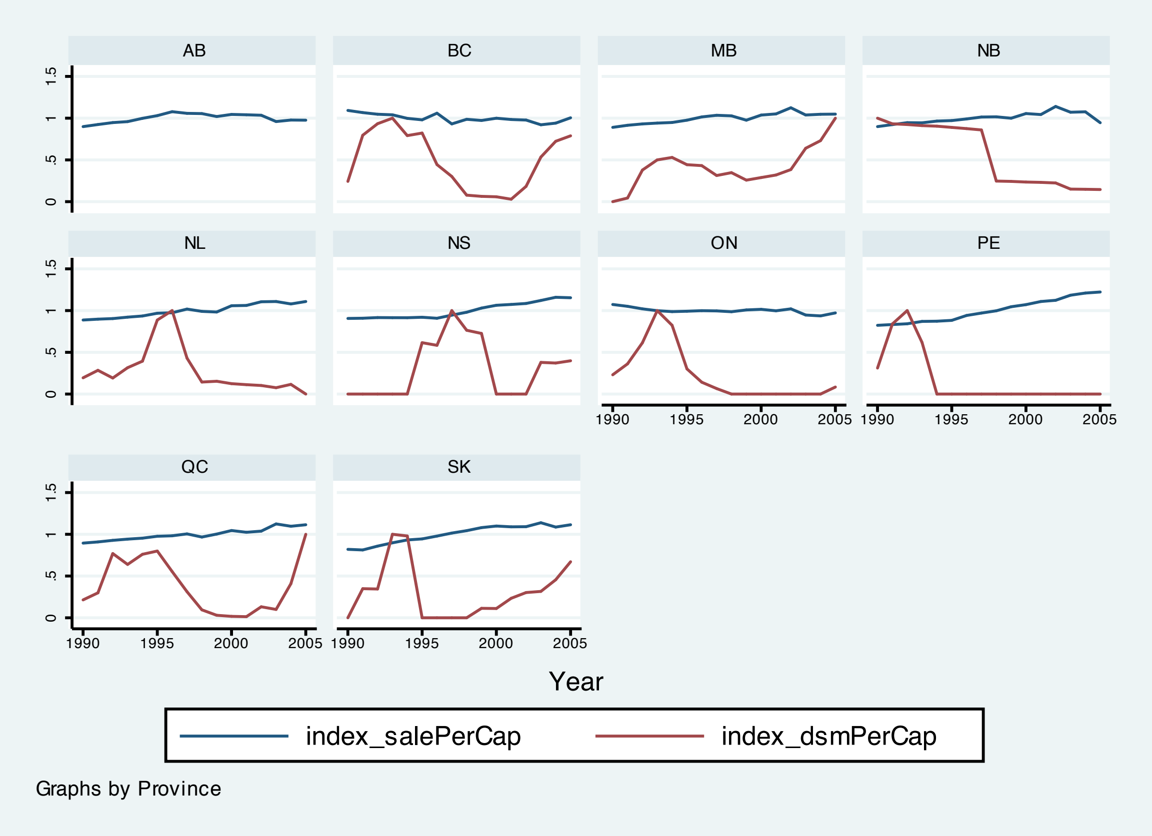

Figure 7.2: Summary of demand side management data, Canadian provinces, 1990-2005. Electricity sales in each provinces are shown as an index with a average value of unity. Demand side management expenditures are shown as a provincial index that takes on a value of unity in the year of maximum provincial DSM expenditure.

7.6 Results

We begin our analysis by testing whether model coefficients for different provinces can be pooled together (i.e., is (7.7) appropriate, or is it necessary to work with (7.6)?). An F-test on the joint coefficient restrictions implied by (7.7) suggests that these are appropriate, so we work with the pooled models (with fixed effects) only in this section.[6]

The first column of Table 7.2 reports coefficient estimates for the fixed effect (7.8) model, with standard errors robust to heteroscedasticity. Most coefficients are generally of

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[6] F = 0.5563, df1 = 85, df2 = 50, p=0.991.

the expected sign, and all except the coefficient on demand side management expenditures and on cooling degree days are significant at standard levels. The results suggest a short run price elasticity of -0.06 and a long run price elasticity of -0.2. These estimates are fairly consistent with other recent work. For example, in a recent study of US electricity demand Alberini and Fillipini (2010) find a price elasticity of -0.09 to -0.15 in the short run and -0.43 to -0.73 in the long-run. In a meta-analysis, Espey and Espey (2004) report a mean short run price elasticity of -0.35 and a mean long run elasticity of -0.85, but note that there is significant variance in both of these estimates. Our estimated income elasticity is likewise somewhat below published results, at 0.14 in the short run and 0.47 in the long run. For example, in the same meta-analysis, Espey and Espey (2004) report a mean short-run income elasticity of 0.28 and a long-run elasticity of 0.97. Counterintuitively, the sign on the substitute energy price is negative and significant, implying that increases in the price of substitute fuels are associated with reductions in the consumption of electricity. This contradicts other studies, which typically find that electricity and other heating fuels are substitutes rather than complements (Serletis et al., 2010). More heating degree days are associated with larger electricity sales in the model, which makes sense: a one percent increase in the number of heating degree days is associated with about a 0.1 percent increase in electricity sales. In contrast, the coefficient on cooling degree days is not significant (although it is of the correct sign). Finally, the coefficient on the percent of sales going to the residential sector is significant and of the correct sign, and suggests that as the residential sector makes up a larger share of total sales, the utility's sales fall.

The coefficient on the demand side management variable is close to zero and statistically insignificant. Despite the fact that the variable is not precisely estimated, it is possible to estimate confidence bounds on the effectiveness of DSM over the period analyzed. In the short run, the standard error on the coefficient suggests a 95 percent confidence bound of [-0.00054, 0.00079]. This implies that a $6 per capita DSM expenditure, which was the sample mean during 1990-2005, is estimated to increase electricity consumption in the short run by 0.00075 percent (with a 95 percent confidence interval of [-0.0032,0.0047]). In the long run, the same expenditure is estimated to increase electricity consumption by 0.0025 percent (with a 95 percent confidence interval of [-0.018,0.023]).[7]

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[7] The confidence interval of the long-run response to demand side management expenditure is the ratio of two random variables, and so was determined by bootstrapping with 1000 replications.

Table 7.2: Regression results for demand side management expenditures

	LSDV	LSDVAR1	LSDVc
Lagged log of per capita sales	0.7005***	0.6329***	0.7722***
	(0.0949)	(0.0622)	(0.0631)
Log of GDP per capita	0.1362**	0.1433***	0.1110***
	(0.0441)	(0.0411)	(0.0405)
Log of electricity price	-0.0637*	-0.0820*	-0.0664
	(0.0306)	(0.0444)	(0.0455)
Log of substitute energy price	-0.0358**	-0.0349**	-0.0345**
	(0.0144)	(0.0145)	(0.0144)
Log of heating degree days	0.1128*	0.1245**	0.1115**
	(0.0594)	(0.0480)	(0.0509)
Log of cooling degree days	0.0031	0.0061	0.0030
	(0.0045)	(0.0069)	(0.0059)
Log of percent sales to residential sector	-0.0864*	-0.0969***	-0.0705**
	(0.0409)	(0.0301)	(0.0287)
Per capita demand side management	0.0001	0.0002	0.0000
	(0.0003)	(0.0007)	(0.0007)
N	150	140	150

** p<0.1 ** p<0.05 *** p<0.01*

It is useful to consider the economic implications of these findings. By weighting the estimated long-run (cumulative) percentage savings resulting from demand side management expenditures by the quantity of electricity sales at each utility in each year, we obtain an estimate of the total reduction in electricity sales resulting from DSM.[8] When this estimate is divided by the total expenditures on demand side management, we obtain an estimate of the cost of reducing electricity demand through DSM expenditures.[9] Because the parameter on DSM is not estimated precisely in the model, we apply these calculations to the 95 percent confidence bounds suggested by the estimate, which allow us to identify a range of DSM savings and cost effectiveness that are consistent with our data and model. Based on these calculations, we find that DSM expenditures from 1990 to 2005 have resulted in changes in electricity sales between -1186 GWh (a saving) and +1519 GWh (an increase). Both of these are trivial in size compared to total Canadian domestic utility sales of over 500 TWh. The lower 95 percent confidence interval implies a cost effectiveness of reducing electricity demand through demand side management of over \$2/kWh, much higher than other sources of supply (we do not calculate a cost-effectiveness for the upper end of the confidence interval, since this estimate suggests that DSM expenditures are associated with electricity demand increases, rendering a cost-effectiveness calculation meaningless).

The second two columns of Table 7.2 implement alternative estimation strategies described earlier, designed to correct for serial correlation in the model residuals and to deal with bias introduced as a result of the lagged dependent variable. Accounting for serial correlation using a first-order autoregressive error term does not substantially change parameter estimates (see the second column of the table). The coefficient for demand side management is actually reduced in absolute value in this approach, and the confidence interval is somewhat widened. These changes do not affect the conclusions drawn above. Correcting for the bias caused by inclusion of the lagged dependent variable using the method proposed by Kiviet (1995) does affect parameter estimates somewhat. In particular, the coefficient on the lagged dependent variable increases substantially, implying that

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[8] This estimate is based on the weighting scheme proposed by Auffhammer et al. (2008) and implemented by Arimura et al. (2009). Formally, cumulative per capita savings in kWh S are calculated for each utility in each year based on model parameters: $S_{it} = \frac{\delta}{1-\lambda} kWH_{it} DSM_{it}$.

[9] To determine cost effectiveness, total expenditures on DSM across the sample are divided by the sum of total savings: $CE = \frac{\sum_i \sum_t DSM_{it} POP_{it}}{\sum_i \sum_t S_{it} POP_{it}}$.

electricity consumption is more persistent than suggested in previous models.[10] The long-run price and income elasticities in this new model are 0.29 and 0.48 respectively, somewhat higher than in the uncorrected models, and more consistent with the evidence from other studies described above. However, the coefficient on demand side management expenditures remains statistically insignificant and economically small (even when evaluated at the bounds of the confidence interval), again suggesting that demand side management expenditures have not played a substantial role in influencing electricity demand in Canada and that the cost of reducing demand through demand side management programs has been high.

In sum, all of the models that were estimated suggest that demand side management expenditures have had minimal impact on electricity demand. Our best estimate, from our preferred model, is that demand side management expenditures in Canada, which averaged roughly $6 per person per year across all utilities during our sample timeframe, have resulted in an increase of electricity demand of about one hundredth of a percentage point, an economically very small amount. As a result, we estimate that reductions of electricity consumption using demand side management have cost significantly more than estimated by utilities. Although coefficients on DSM expenditure are estimated imprecisely, standard confidence bounds around the estimates do not include low-cost estimates of demand side management that are estimated by utilities themselves. Our data do not allow us to suggest why this is the case, but we speculate that a combination of underestimating free-ridership rates and neglecting to account for rebound effects are the likely reasons. In particular, the estimates from our model suggest an upper bound for the direct rebound effect of about 30 percent, and other studies cited in this paper have shown that free ridership rates are often 50 percent or higher. The combination of these two effects could worsen the cost-effectiveness of a utility DSM program to the degree that we have reported here.

Several potential problems may contaminate our findings. First, although demand side management expenditures are treated as an exogenous variable here, it is possible that they could be endogenous. A possibility is that jurisdictions with high electricity sales are more likely to implement DSM programs, or else that in years when electricity sales are high, DSM programs are more likely to be implemented. If either of these is the case,

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[10] The difference in coefficients is very similar to that suggested by Nickell, who determined that bias in the parameter λ using the demeaned approach is approximately $-\frac{1+\lambda}{T-1}$, which works out to -0.11.

our estimates of the impact of DSM are likely to be biased towards zero. In theory it is possible to find an instrument to account for this source of endogeneity, but in practice, especially given our small sample, we could not find an appropriate one. However, we feel that it is unlikely that DSM is endogenous in our formulation. DSM effort in Canada has been driven especially by the regulatory environment and by personalities, and anecdotal evidence as well as our experience in the industry suggests that causality in the relationship runs from DSM expenditures to electricity sales, and not the reverse.

A second problem that our study could suffer from is that it does not account for regulations, standards, and policies that affect electricity sales other than utility demand side management. For example, both provincial and federal governments offer tax credits to encourage energy efficiency, as well as implement standards and regulations that affect energy sales. Local and provincial governments also regulate land use and building codes, each of which can affect energy consumption. If changes in these variables are correlated with demand side management expenditures, then omitting them from the model will cause the coefficient on the DSM variable to be biased. In particular, if other policies are implemented simultaneously with DSM expenditures, then the (absolute value of) the DSM coefficient will be biased upwards. On the other hand, if government regulations are used as a substitute for DSM expenditures, such that they increase in intensity when DSM intensity is reduced, then the DSM coefficient will be biased towards zero. We have no reason to suspect either case. The federal government regulates appliances and industrial equipment on a regular cycle in Canada, with new regulations issued every year and existing regulations updated every several years.

Third, we note that our data on demand side management expenditures include all demand side management - in particular it includes both load management expenditures as well as energy efficiency expenditures. Since load management expenditures are not aimed at curtailing electricity demand explicitly, including these could lead us to suggest that demand side management is more costly than is really the case. However, in utilities that were able to provide us with data (as well as in US utilities), load management expenditures amounted to less than 25 percent of the total, so error in our estimates should not be too severe, and in particular should not change the nature of our conclusions.

7.7 Conclusions

The estimates from our analysis indicate that in aggregate DSM expenditures by Canadian electric utilities have had only a marginal effect on electricity sales. Thus, our mean estimates for the cost effectiveness of DSM spending, for the period covered by our study, suggest that the costs for reducing overall electricity demand through DSM subsidies are high in comparison to the values estimated by utilities themselves. Additionally, although the coefficient on DSM spending in our estimated models is not estimated precisely, at conventional levels of statistical significance we are able to reject the DSM cost effectiveness values that have been estimated by the utilities.

The method we use, which because of its aggregate nature directly accounts for the net effect of free ridership, rebound effect, and within-jurisdiction spillover, provides a useful comparison to utility estimates of DSM effectiveness. However, because of the aggregate nature of our approach, we are not able to determine if the cost effectiveness of DSM has changed over time, or whether DSM expenditures in some utilities or sectors are more effective than those in others. Indeed, our data set almost surely includes some DSM programs that are very cost effective, as well as others which are not. Our analysis is only able to estimate the aggregate effectiveness and cost effectiveness of all DSM programs in Canada over a 16-year period.

It is important to emphasize that the cost effectiveness estimates generated by this research do not indicate the full technico-economic cost of improving energy efficiency, but rather reveal the cost of pursuing energy efficiency by a utility, which is typically conducted with subsidies. Subsidies are less effective than often assumed because they cannot avoid distributing the subsidy to those who would have undertaken the energy efficiency measure in the absence of the subsidy. These free riders weaken the effectiveness of the subsidy. Additionally, the rebound effect, which occurs as consumers adjust purchases in response to changes in relative prices, further erodes the effectiveness of an energy efficiency subsidy. Our analysis is suggestive that free ridership and rebound may have been substantial during the period of electric utility DSM subsidies covered by this study. This suggests that policy initiatives that rely on subsidies to promote energy efficiency may be much less effective than their supporters claim. This holds equally for government subsidy programs and for private subsidy programs, such as offset programs currently associated with efforts to reduce GHG emissions via subsidy.

The results should not be taken, however, to imply that investments in energy efficiency are undesirable from a social perspective. In estimating the cost-effectiveness of DSM programs, electric utilities are confined to a narrow definition of cost effectiveness that typically excludes environmental and social externalities. If these are taken into account, there is considerable research indicating that energy efficiency remains cost effective relative to new conventional generation from a social perspective. The challenge for utilities, governments and concerned individuals is to find policies that will actually ensure greater energy efficiency than that which naturally occurs as the capital stock evolves.

Chapter 8

Conclusions

8.1 Summary of papers

Substantially reducing global greenhouse gas emissions has been and will continue to be a major challenge, especially because of the global nature of the problem and the lack of strong international institutions.

In addition to these and other general difficulties associated with addressing the climate change problem, in Canada and other developed countries, policy makers hoping to implement policies to substantially reduce emissions have to grapple with several domestic concerns: that such policies will reduce overall economic growth and the quality of life for Canadians; that such policies will inhibit the ability of Canadian firms to successfully compete with international rivals; and that such policies will fall disproportionately on certain demographic groups, economic sectors, or regions.

In this thesis, I aim to address some of these concerns. To do so, I develop a series of environmental-economic computable general equilibrium models of the Canadian economy, and simulate several different types of policies designed to reduce greenhouse gas emissions. My general finding is that it is possible to design greenhouse gas mitigation policies that achieve substantial reductions in greenhouse gas emissions while at the same time addressing particular concerns expressed in the previous paragraph. While it appears likely that there will be a real economic cost associated with implementation of climate policy, decision makers have a high degree of latitude in choosing how to allocate this burden throughout society, and should be able to design a politically-acceptable policy that addresses many of the above concerns and that also maintains environmental integrity. I also conduct an econometric analysis of a particular policy that has been applied over the past two decades in Canada and that involves subsidies to promote energy efficiency. I find that this policy has had limited effectiveness and high cost, again confirming the importance of good policy design to achieve environmental targets at acceptable cost.

In the first paper, I examine the issue of sub-global climate change policies. The paper is motivated by the strong likelihood that wealthy countries like Canada will be pressured to implement climate change abatement policies prior to adoption by poorer countries, as well as by the fact that even between wealthy countries it is unlikely that climate change policies will be uniform. Such a scenario raises concerns that energy intensive firms in Canada could migrate to other countries with less stringent environmental regulations. This dynamic raises at least two concerns: first, that employment and economic output of key energy-intensive sectors will be reduced as firms in these sectors shift to more lightly-regulated countries; and second, that the environmental integrity of the policy will be compromised as firms move to a different jurisdiction to avoid regulation rather than reducing emissions.

My paper seeks to answer two questions: first, to what degree are these concerns about shifting competitiveness warranted, and second, is it possible to design policies such that greenhouse gas emissions are reduced without the loss of international competitiveness by key energy-intensive firms? To answer these questions, I build a dynamic computable general equilibrium small open economy model of Canada, and consider unilaterally-applied greenhouse gas policies. I find that several energy-intensive sectors could suffer loss of market share to foreign firms with unilaterally-applied carbon policies - notably the chemicals, refined petroleum products, primary metal, and agriculture sectors. To answer the second question, I consider six alternative climate policies designed to protect key industrial sectors from loss of competitiveness while maintaining a constant level of emission reductions. I find that some of these are successful in maintaining the international competitiveness of the energy-intensive sectors, but that most are associated with tradeoffs, either by concentrating the burden of emission pricing on other sectors, or by reducing the overall level of economic output. The challenge for policy makers is to choose from these tools in a way that is politically acceptable.

In the second paper, I examine the distributional incidence of domestic climate change policies. I conduct the analysis with a static computable general equilibrium model that distinguishes between a number of different classes of households and that contains a significant amount of detail in its representation of the labour market as well as of the ownership of other factors of production. By representing factor ownership in detail, I can model the process by which the incidence of the policy can be passed backwards to owners of factors of production as well as forwards onto increases in the price of consumer goods. Simulations using the model show that the design of the climate policy has a significant influence over its distributional incidence. In particular, when a cap and trade policy is implemented and revenues from auction of allowances are distributed in equal per-household amounts, the level of income inequality in society is reduced. Conversely, when a cap and trade policy is implemented and revenues from allowance auction are used to lower the personal income tax in a revenue-neutral manner, the level of income inequality in society is increased. Because this second policy results in a greater level of overall economic output, it is possible to evaluate the tradeoff between equity and efficiency. I find that using greenhouse gas policy to reduce the Gini coefficient (a measure of income distribution) by 1 percent is likely to come at a cost of about 1.2 percent of gross domestic product. This tradeoff is useful information for policy makers in designing greenhouse gas policies.

In the third chapter, I explore a single policy design in some detail. This is the tradable emission performance standard that has so far dominated Canadian government proposals for market-based climate change policies for large industry. Under this policy design, government sets a limit on the emission intensity of industry sectors, and allows firms that achieve an emission intensity lower than the requirement to sell permits to those that fail to achieve their requirement. The policy differs from a traditional cap and trade system in that it encourages firms to increase their level of output (since this reduces emissions intensity). To evaluate this proposed policy, I compare it to a traditional cap and trade system by building a simple theoretical model and by evaluating it using a dynamic computable general equilibrium model. I show that the tradable emission performance standard has certain advantages over a traditional cap and trade system. In particular, it has the potential to limit the loss of international competitiveness of energy intensive sectors, it can reduce negative interactions with pre-existing taxes, and it may encourage the faster development of new technologies to reduce emissions. These potential benefits do come at a cost, however. The tradable emission performance standard system is less transparent, fails to maintain a fixed level of emissions when the level of economic output deviates from the forecast, and imposes larger overall costs compared to a traditional cap and trade policy with auctioned permits and a revenue-neutral tax recycling scheme. Once again, the detailed design of climate policies is shown to have a substantial impact on their overall effect.

In the fourth paper, I conduct an evaluation of demand side management programs by Canadian electric utilities. Between 1990 and 2005, Canadian utilities spent approximately $3 billion on such programs. However, despite the relatively large expenditure, the overall impact of such spending is not possible to observe directly and remains the subject of significant controversy. In this paper, I take advantage of the significant temporal variation in demand side management expenditures in each province in Canada to infer the effectiveness of these programs at reducing electricity demand. I use a panel data structure to augment my sample size and to address unobserved heterogeneity, and a partial adjustment model to account for the fact that electricity demand changes slowly as a result of changes in economic conditions. My analysis suggests that demand side management programs have had negligible impact on overall electricity demand. As a result, I find that the cost effectiveness of these programs is much worse than suggested by utility evaluations. I conclude that, since most demand side management programs are conducted through incentives, it is likely that free-riders and rebound have eroded most of the potential savings. Although this study is not directly related to climate change policy, it does have important implications for this field, since many existing and proposed climate change policies feature a similar use of subsidies to promote energy efficiency.

8.2 Extensions

Taken together, these papers confirm the critical importance of careful design of market-based climate change policies in achieving substantial greenhouse gas reductions at an acceptable cost. And together, they help to establish how a successful market-based climate might be structured, assuming that such a policy was designed to reduce emissions while simultaneously maintaining economic growth, avoiding the exacerbation of disparities in income, and avoiding losses of international competitiveness for energy-intensive sectors. In what follows, I venture beyond the direct conclusions reached in the individual papers that make up this thesis, and develop an outline for what I believe would be an effective, efficient, and fair national climate change policy.

Such a policy would have at its foundation a broad carbon price covering all carbon dioxide emissions in the economy.[1] Although economists are often ambivalent about the choice between carbon taxes and cap and tradable permit systems, I prefer the former in this scenario, for several reasons that mostly go beyond the analysis presented in this thesis. First, because from an administrative perspective, a carbon tax is very simple to implement. Governments already collect taxes on most energy products, so the collection mechanism is already established; the implementation of a carbon tax involves primarily changing the rate of such taxes, and little other new infrastructure or bureaucracy. As such, a carbon tax policy can be implemented quickly, whereas a cap and trade policy is likely to take much longer to develop and implement (this has been borne out in recent Canadian and international experience). Second, carbon taxes are more transparent to the public than equivalent cap and trade systems. In the former, the price on carbon is evident, stable, and gradually rising. In the latter, the price on carbon is implicit, possibly volatile, and can be traded in a variety of markets at a variety of prices (secondary markets, futures markets, etc.), which makes the nature of the policy less obvious to the public. While there may be political economy gains from reducing transparency, I think that these are likely ephemeral - eventually the public will conclude that carbon policies affect prices of consumer goods, whether implemented through a carbon tax or cap and trade system. Third, I believe that carbon taxes are likely to be less costly to the economy than a cap and trade system. Several studies have shown that transaction costs associated with cap and trade systems can be substantial, while it is likely that transaction costs associated with carbon taxes are minimal. Finally, because the marginal abatement curve is likely steeper than the marginal benefit curve at the desired level of emissions abatement, errors in choosing the optimal tax rate are likely to result in smaller overall costs than errors in choosing a cap in a cap and trade scheme.

A key issue that was tackled in this thesis concerns how revenues raised from such a policy could be used to meet various secondary goals. Since the optimal mix of uses for the revenue depends on the relative weights placed by society on these various secondary

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[1] Carbon dioxide accounts for roughly four fifths of all greenhouse gas emissions in Canada. Non-carbon greenhouse gases could be included as well where possible, although measurement difficulties sometimes preclude the use of conventional pricing instruments.

goals - information I do not have - here I describe a revenue mix that I would find satisfactory, and make no claims about whether the mix is optimal from a social perspective. First, I would use part of the revenue from the policy to ensure that the policy avoided exacerbating income disparities in society. My analysis suggests that this would be possible by distributing roughly 30 percent of the revenues from the carbon tax in lump sum, on an equal per-household basis. If instead, revenues were targeted directly at low-income households (rather than broadly at all households), it would be possible to achieve this goal with less consumption of the overall carbon tax revenue. Second, I would aim to mitigate impacts on the international competitiveness of energy-intensive industries. Based on my analysis, I would choose to use part of the revenue to provide output-based rebates to firms that are energy-intensive and also trade-exposed. Output-based rebates offer a similar incentive as tradable performance standards examined in one of the papers presented here, since like tradable performance standards, they reduce the consumer price of output through an implicit subsidy on production. My analysis suggests that this instrument could be effective in promoting the international competitiveness of Canadian energy-intensive firms, even under a unilaterally applied carbon policy. Finally, I would use the remainder of the revenues from the carbon policy to reduce the rate of pre-existing distortionary taxes in the economy. My analysis, as well as that of others, suggests that corporate income (capital) taxes are amongst the most distortionary in the economy, and so my first choice would be to use the remainder of the revenue to lower these taxes. If, for political acceptability reasons, this was not possible, I would use the revenue to reduce both the corporate income tax and the personal income tax.

By adopting this type of broad and transparent climate change policy, Canada could substantially reduce its emissions without major impacts on economic output, international competitiveness, or income distribution. Even if Canada were to develop and begin implementing such a policy in advance of other countries like the United States, my analysis suggests that economic impacts would be manageable. Since global governance of climate change continues to be limited, such a conclusion is reassuring. Even without a binding international environmental agreement to govern the atmosphere, it may be possible for nation-states to gradually implement domestic policies to reduce emissions at low cost, and gradually foster the development of a cooperative effort to reduce emissions internationally. Ultimately, the conclusions in this thesis offer some optimism regarding the potential for deep reductions in global emissions to avoid dangerous climate change.

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