

THE EFFECT OF CLIMATE POLICIES ON LOCAL AIR POLLUTION:  
DESIGN AND CANADIAN APPLICATION OF A MODELLING TOOL

by

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## **ABSTRACT**

In 2002 Canada ratified the Kyoto Protocol, committing to reduce greenhouse gas emissions (GHGs) to combat climate change. Leading up to ratification, and continuing today is a heated debate surrounding the cost of climate policy.

Evaluating the costs of reducing GHGs is complex, and estimates vary depending on how costs are defined, how uncertainty is treated, and whether or not ancillary costs and benefits are considered. Ancillary benefits or costs result in addition to the effects of the climate policy on its stated target. An important ancillary effect is the potential for climate policies to impact local air pollution. Caused by criteria air contaminants (CACs), local air pollution holds serious consequences for regional environments and human health.

A modelling tool was developed to simulate, through an integrated representation of the Canadian economy and energy system, the GHG-reducing actions induced by climate policy and the associated changes in CAC emissions. Criteria were established characterizing the ideal energy-economy ancillary effects estimation tool, including: technological explicitness, preference incorporation, disaggregated calculation of CAC emissions, and spatial resolution. The CIMS model served as the base modelling tool, and was enhanced with technology specific CAC emission factors. Incorporating CACs into CIMS represents the first attempt at estimating CAC emission changes in Canada with a behaviourally realistic, technologically detailed model.

The CAC pollutants added to CIMS include fuel-based, process-based, and fugitive sources of nitrogen oxides (NO<sub>x</sub>), sulphur oxides (SO<sub>x</sub>), volatile organic compounds (VOCs), carbon monoxide (CO), and particulate matter (PM). The resulting tool can track changes in CACs and GHGs at the technology level and report the cumulative effect on regional emissions.

The analysis focuses on Ontario and Windsor-Quebec corridor in particular - and evaluates the effect of a range of GHG shadow prices on CAC emissions. Highlighted by the analysis is the fact that actions to reduce GHGs do not always result in CAC reductions, and that a technology-specific model can provide a deeper understanding of why these tradeoffs exist and how to plan around them.

## **Dedication**

For my parents,  
who always made me feel  
like I could do anything.

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## Introduction

For the past 15 years there has been a growing focus in the international arena on the threat of climate change and the role of increasing anthropogenic emissions of greenhouse gases (GHGs). The government of Canada has stated that climate change is ‘the ultimate sustainable development issue’ and in 2002 ratified the Kyoto Protocol, an international agreement that established GHG emission reduction targets for Canada of 6% below 1990 levels by 2008-2012 (Government of Canada, 2002). Concurrently, concerns about local air pollution and the serious consequences for regional environments and human health have increased.

In 1998 the federal and provincial governments initiated the National Climate Change Process (NCCP) to evaluate the cost of different options for achieving Kyoto emission reductions. A central focus of the process is the cost effectiveness of policies as well as the distribution of costs across the provinces and territories (Government of Canada, 2002). However, the evaluation of the costs of GHG reduction policies is not straight-forward. Cost estimates vary considerably with differing definitions of costs, treatment of uncertainty, and the consideration of ancillary costs and benefits.

A key component in evaluating the costs of reducing GHGs, is accounting for the ancillary effects that may occur and to what extent they offset, or further inflate, these costs. Ancillary effects are the benefits or costs that result in addition to the effects of the climate policy on its stated target (Pearce, 2000; Burtraw and Toman, 2001). One ancillary effect focused on in the literature and climate debate is the potential for GHG-reducing actions to affect the production of criteria air contaminants (CACs). CACs contribute to local air pollution concerns such as acid rain, and the formation of photochemical smog which in turn impact natural and human systems at considerable cost to society.

Some researchers have suggested that benefits from improved local air quality could be larger than the primary benefits associated with CO<sub>2</sub> abatement (Ekins, 1996). However, ancillary effects are often omitted from the analysis and debate surrounding GHG policy analysis because of the large uncertainties and regional differences involved in their estimation. Without an understanding of the potential effect of GHG policies on

local air pollution decision makers are forced to craft policies based on incomplete information (Davis et al., 2000). By failing to take the full costs and benefits into account, the resulting climate policies may miss the opportunity to minimize the costs to society.

## **1.1 Background**

Greenhouse gases and CACs, the groups of pollutants that contribute to climate change and worsening local air quality, are suited for simultaneous evaluation in climate policy analyses. Both GHGs and CACs are produced as a byproduct of fossil fuel combustion (Ayres and Walters, 1991). Furthermore, each of these pollutant groups causes significant economic, environmental and social impacts. Understanding the nature of these impacts and the differences and similarities between them further underlines the importance of considering both pollutant groups when evaluating environmental policy.

### **1.1.1 Greenhouse Gases and Climate Change**

Greenhouse gases (GHGs) accumulate in the atmosphere and absorb infrared radiation from the earth that would otherwise be released to space, disrupting the cooling and heating cycles of the ecosphere (IPCC, 1996b). Some GHGs occur naturally, however, the increasing atmospheric concentrations of GHGs that are implicated in climate change are due to human activities such as deforestation and fossil fuel combustion. Furthermore, GHGs tend to mix evenly in the atmosphere, meaning that one unit of GHG emitted in Canada is one unit emitted globally in terms of its effect on climate. While the impacts of climate change are typically slow and long-term, they may be quite severe. Some of these impacts include: increased flooding in some areas and droughts in others, the migration of ecosystem boundaries, displacement of people, and increased pestilence and disease (IPCC, 1996a). The long-term impact of climate change on ecosystems and human welfare may be severe and is quite uncertain.

In order to understand the key factors that affect GHG emission production and to help identify ways to target GHG emission reductions, decomposition equations are often used. One such equation, called the “Kaya Identity”, is displayed in equation 1. The Kaya Identity asserts that changes in GHG emissions will result from changes in the GHG-intensity of energy use in the economy ( $GHG/E$ ), the energy intensity of economic production ( $E/Q$ ), the economic output per-capita, and the population size ( $P$ ). The two final terms (economic output per-capita and population size changes) are considered much more difficult for governments to influence for mainly political, social, and economic reasons (Jaffe et al., 1999; Jaccard et al., 2002). Hence, policies hoping to stimulate a reduction in GHG emissions tend to focus more on the energy intensity of economic production ( $E/Q$ ), and the GHG-intensity of energy use in the economy ( $GHG/E$ ).

**Equation 1. The Kaya Identity**

$$\% \Delta GHG = \% \Delta \frac{GHG}{E} + \% \Delta \frac{E}{Q} + \% \Delta \frac{Q}{P} + \% \Delta P$$

where:

$GHG$  = greenhouse gas emissions

$E$  = unity energy

$Q$  = measure of economic output

$P$  = population

**1.1.2 Criteria Air Contaminants and Local Air Pollution**

Like GHGs, CACs are both naturally and human produced, and the primary anthropogenic source is as a byproduct of fossil fuel combustion. CACs include carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), sulphur oxides (SO<sub>x</sub>), volatile organic compounds (VOCs), and particulate matter (PM). The most commonly studied CACs are

SO<sub>x</sub>, NO<sub>x</sub>, VOCs and the smaller fraction of particulate matter (PM<sub>2.5</sub>)<sup>1</sup> as these are known to have serious health impacts and contribute to the formation of acid rain and photochemical smog (Burtraw and Toman, 2001). Carbon monoxide is more important as an indoor air pollutant.

In comparison to GHGs, CACs differ in terms of the nature of their production, but also the nature of their impact on the environment. The production of CACs is more complicated than GHGs because the amount of pollutant emitted is less directly related to the quantity of fuel combusted. For example, the quantity of NO<sub>x</sub> emitted per unit of fuel combusted will vary for different sizes of industrial boilers running at different operating temperatures (U.S. EPA, 2000). Thus, variations in process characteristics (like operating temperature) have a greater influence on the magnitude of CAC emissions than GHG emissions.

Another important difference between GHGs and CACs is the environmental effect they have. Where GHGs mix uniformly in the atmosphere, CACs behave in a more localized manner. Notably, CACs contribute to the formation of acid rain and photochemical smog. Impacts associated with smog are reduced visibility and a number of health problems including increased respiratory distress<sup>2</sup>. Acid rain contributes to serious environmental and structural degradation by defoliating vegetation, acidifying lakes, and damaging infrastructure. The subsequent costs of the mortality, morbidity, reduced visibility, and structural damage can be quite high (Burtraw and Toman, 2001).

While the impacts of CACs are more regional or local in nature, and are felt more immediately than those from GHGs (Ekins, 1996; Burtraw and Toman, 1997; Davis et al., 2000; Burtraw and Toman, 2001), their common link to fossil-fuel combustion and economic activity dictates that actions to reduce production of one will affect the production of the other. Hence, the design and evaluation of policies aimed at reducing

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<sup>1</sup> Particulate matter is categorized by the size of the particles, and includes particles with a diameter less than or equal to 10 microns (PM10) and less than or equal to 2.5 microns (PM2.5).

<sup>2</sup> See Davis et al. (2000) for a more complete discussion of the health effects related to CACs.

GHGs must carefully consider the effect of resulting actions on CAC production and the economic and environmental ramifications. Researchers have emphasized that an evaluation of the ancillary effects of climate policies on CAC emissions should not assume that these effects will necessarily be ‘benefits’ (Davis et al., 2000; Burtraw and Toman, 2001), as is commonly the case in the literature. Rather, careful attention should be paid to understanding which GHG-reducing actions will reduce CACs, and which actions will exacerbate them.

## **1.2 Why Ancillary Effects Matter to Climate Policy Design**

Understanding the ancillary effects of climate policy is important for many reasons, including the potential to affect the speed at which climate policies are implemented, affect the planning of policy incidence, shift the relative desirability of policy options that target trading versus domestic reductions, and alter the ‘no regrets’ level of abatement (Davis et al., 2000; Krupnick et al., 2000; Pearce, 2000; Burtraw and Toman, 2001).

The importance of understanding the effect of GHG policy on local air pollutants is enhanced by the difference between the impacts of the two pollutant categories. Fighting climate change is a key aspect of federal environmental policy, yet is an uncertain goal with diffuse, intangible benefits that will be felt over the long term. Local air pollution is more tangible and equally severe (Ekins, 1996), only on a different spatial and temporal scale. Hence, if concentrated local benefits related to air quality can be realized from implementing GHG measures, climate policy implementation will likely occur in a more timely fashion (Pearce, 2000).

Furthermore, because of the local impact of CACs, the planning of policy incidence becomes more complicated than if GHGs are considered alone. First, if densely populated areas are targeted with more GHG reductions, the potential ancillary benefits could be much greater. Moreover, consideration must be given to existing international transboundary agreements, such as the Canada-United States Air Quality Agreement, to

ensure that GHG policies do not result in increased emissions of pollutants targeted in these agreements (Heintz and Tol, 1996; Pearce, 2000). In the Canada-United States Air Quality Agreement both countries committed to reductions of NO<sub>x</sub> and SO<sub>x</sub> emissions (International Joint Commission, 2002); therefore, if a climate policy caused increased emissions of NO<sub>x</sub> or SO<sub>x</sub> this could place Canada in contravention of the agreement.

Considering the ancillary effects of climate policies also calls into question the relative desirability of targeting domestic versus international GHG measures. For example, a flexibility mechanism incorporated into the Kyoto Protocol is an international system of tradable permits (Government of Canada, 2002). When ancillary effects are considered, nations that would be ‘permit-buyers’ may re-evaluate their choice to invest in reductions in other countries when they could reap the additional benefits of improved local air quality associated with more domestic GHG reduction measures (Pearce, 2000; Lutter and Shogren, 2002).

Finally, and perhaps most importantly, considering ancillary effects can alter the level of ‘no regrets’ GHG abatement. ‘No regrets’ refers to the level of abatement that can be achieved if all GHG measures with no net cost to society are implemented (Dessus and O’Connor, 1999). When monetized ancillary effects are included in the calculation of net costs or benefits they may alter the no regrets level of abatement and thus change the number of measures that could be taken with no net loss to social welfare.

### **1.3 Ancillary Effects Estimation**

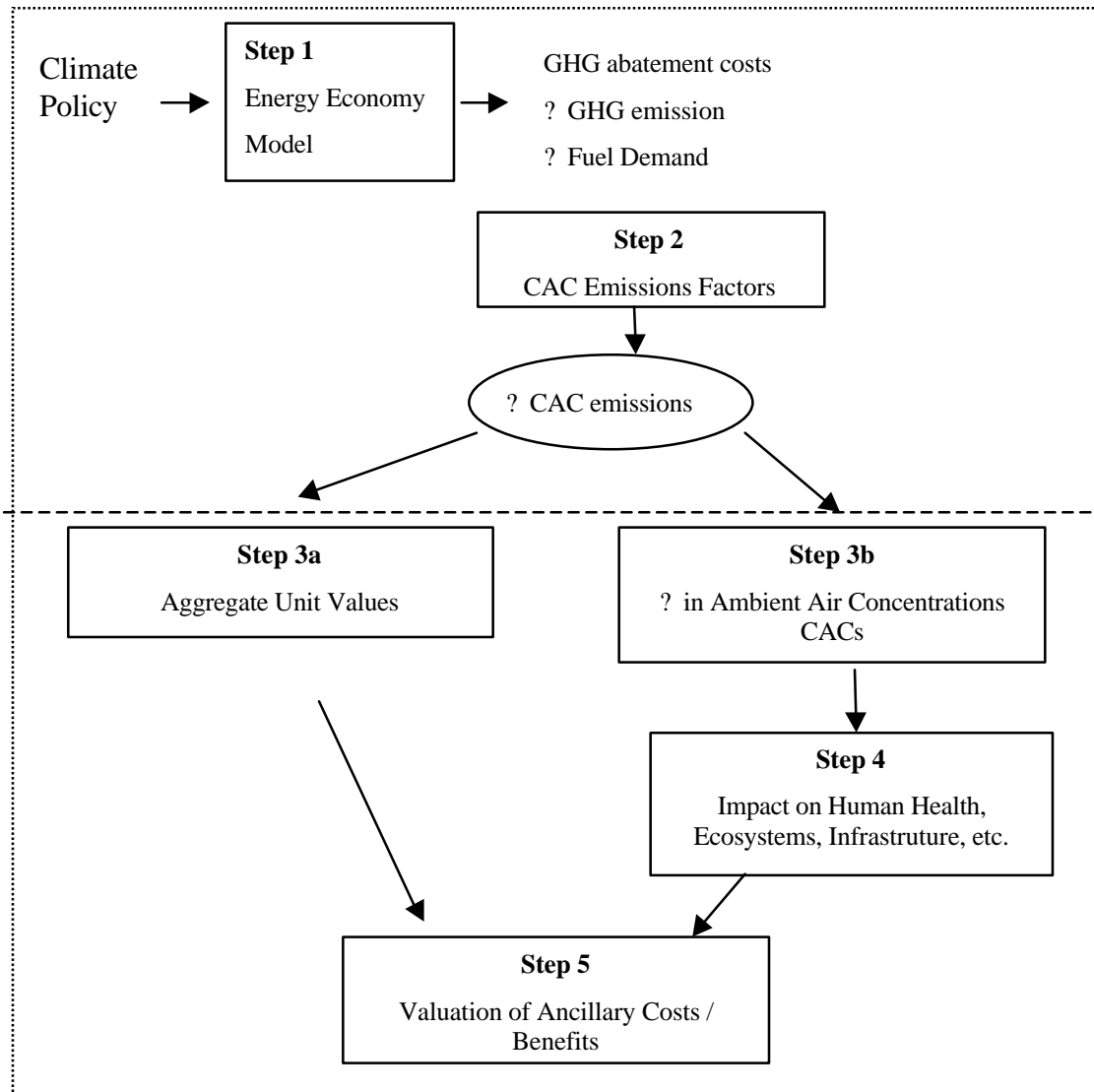
A commonly followed approach to estimating the ancillary effects of climate policies was first suggested by Ayres and Walter (1991), and then further modified by Ekins (1996). This generalized analytical approach to ancillary effects estimation is illustrated in figure 1. The first step is to use CO<sub>2</sub> abatement models (e.g. energy-economy models) to evaluate the CO<sub>2</sub> emission changes and abatement costs, and the underlying changes in fossil fuel demand associated with a climate policy. Energy-economy models describe the relationship between the energy system and the economy and are often used



to estimate the cost and CO<sub>2</sub> emission reductions associated with climate policies. Next, emission factors that relate the CAC emissions associated with the different fuels are used to estimate the resulting changes in CAC emissions.

Once the associated change in CAC emissions is calculated there are two alternative ways to estimate the resulting impact and associated ancillary costs and benefits of a climate policy. The simple approach indicated by step 3a in figure 1 involves multiplying the estimated change in CACs by aggregate unit values that describe the benefits per tonne of pollutant reduced (\$/tonne) (Ayres and Walters, 1991; Ekins, 1996). These aggregate values indicate the ancillary cost or benefit associated with each tonne of GHG reduced by the policy. Alternatively, a more disaggregated, damage-function approach may be followed, as outlined in Burtraw and Toman (1997). In this latter approach (beginning with step 3b), CAC emission changes are translated into changes in the ambient air concentration of the different pollutants, followed by estimation of the effect on human and natural systems. Finally, the impact on human health and the environment is monetized to reflect the final ancillary cost or benefit of the GHG policy (\$ / tonne of GHGs abated). The previously described aggregate approach (step 3a) is less time consuming and involves more simplifying assumptions than the latter, more rigorous damage function approach (Burtraw et al., 1999).

**Figure 1. Analytical pathway for evaluating the ancillary effects of climate policy**



#### 1.4 Energy Economy Modelling and CAC Estimation

As discussed, anthropogenic GHG and CAC emissions are primarily a result of fossil-fuel based energy production and consumption. Therefore, climate policy analysts tend to focus on how policies can change the GHG-intensity of energy ( $GHG/E$ ) and the intensity of energy use in the economy ( $E/Q$ ). The objective of policymakers is to design policies that will induce actors in the economy to switch to energy using and producing

technologies that are more efficient and rely increasingly on renewable or clean energy sources. Correspondingly, policymakers rely on tools to simplify the energy-economy system, and help them understand how policies will affect the choices of actors, and induce technological change (Jaccard et al., 2002).

Energy-economy models are one such type of tool used extensively in the past to evaluate climate policies, and as the first step in ancillary effects evaluation. These models represent the link between the economy and the environment by modelling how technology decisions affect  $GHG/E$  and  $E/Q$ , and how policies can alter these decisions, thereby changing the amount of emissions produced in the economy (Edmonds et al., 2000).

#### **1.4.1 Bottom-up, Top-down and Hybrid Modelling**

Energy-economy models are typically classified as ‘top-down- or ‘bottom-up’ in their approach. Each category of model produces very different estimates of the cost and effectiveness of climate policies. Three assumptions that play a large role in creating the differences between top-down and bottom up model estimates include: a) how costs are defined and subsequently how actors in the economy respond to changing costs, b) how the direction and rate of technology change is represented, and c) how the baseline is defined (Azar and Dowlatabadi, 1999; Edmonds et al., 2000; Jaccard et al., 2003). The following paragraphs review the ‘top down’ and ‘bottom up’ energy-economy modelling approaches with two goals in mind: illustrating how the different treatment of the aforementioned assumptions affect the change in emissions and costs estimated by the these models, and developing a list of criteria that can help evaluate the usefulness of energy-economy models as tools to help evaluate the ancillary effects of climate policy.

##### *Bottom-up*

Bottom-up analysis, most frequently applied by engineers and systems analysts, focuses on the alternative technologies that are available to provide energy services, and how increasing diffusion of these technologies can result in changes in energy use and

emissions. Correspondingly, a detailed account of current and future technologies is included in the model, including cost (financial) and performance (efficiencies) characteristics (Jaccard et al., 1996).

The speed and direction of technology change in bottom-up models is driven by the differences in cost and efficiency of competing technologies. It is assumed that consumers will choose the option with the lowest *ex-ante* (anticipated) estimate of financial costs, causing technologies that are more energy efficient to penetrate relatively quickly because their energy-costs are lower than a similar, less efficient alternative (Edmonds et al., 2000; Jaccard et al., 2003). However, the bottom-up approach is criticized for assuming that the full social cost of switching between technologies can be represented by a simple *ex-ante* estimate of the financial cost differences between these technologies. Technologies are not always perfect substitutes in the eyes of consumers, and may differ in ways that are not captured by a single financial estimate (Jaffe and Stavins, 1994; Jaccard et al., 2003).

There are three main ways technologies may differ which are not captured by financial estimates. First, some technologies are perceived as being ‘risky’, with a greater potential for premature failure and long payback periods (as a result of high upfront costs). The value of not investing in a technology that is perceived as risky is termed ‘option value’: The consumer perceives a gain in value while postponing investment and waiting for additional information to inform their decision. Second, the service provided by two alternative technologies may not be identical in the eyes of a consumer. Jaccard et al. (2003) use the example of traditional incandescent versus more energy efficient compact fluorescent light bulbs. Some people consider the compact fluorescent a less than perfect substitute because of the longer time to reach full illumination, the quality of the light, and the unattractiveness of the bulb. This extra (non-financial) value that consumers attribute to their current preferred technologies is called ‘consumers’ surplus’. Finally, a single point estimate of the financial cost difference of technology options does not incorporate the heterogeneity in costs faced by the consumer. Different consumers in

different locations will face varying acquisition, installation and operating costs.

The failure to account for option value, consumers' surplus and market heterogeneity in bottom-up models when estimating the cost of technology alternatives results in an overestimated willingness of consumers to switch to GHG-reducing technologies. The result is that the social cost of climate policies is underestimated and a prematurely quick and inexpensive improvement in energy efficiency and energy intensity over time is predicted.

Assumptions regarding the baseline scenario (the characterization of the energy economy without a climate policy) also affect the results of bottom-up analyses. Bottom-up models typically assume that the baseline is relatively inefficient due to the presence of market barriers and market failures that hinder the adoption of energy-efficient technologies. For example, there are high transaction costs associated with learning about alternative, energy-efficient technologies as well as in acquiring and operating them which are not captured in the financial cost of a technology - meaning that the market will tend to under-supply them (Jaffe and Stavins, 1994; Jaccard et al., 1996). Bottom-up analysts generally assume that the policies to correct for these barriers and failures will have no net costs to society (as they are restoring economic efficiency by increasing the supply of more efficient technologies), and that other costs associated with these policies are minor (Edmonds et al., 2000).

Finally, because bottom-up models incorporate considerable technological detail they are less able to incorporate elements of economic feedback which is required to evaluate the macro-economic effect of policies. Instead, these models usually provide only a partial equilibrium (equilibrium is reached in one or a sub-set of economic sectors), in response to GHG policies (Jaccard et al., 2003). Thus, the full macroeconomic effects of a GHG policy targeted on a single sector may not be adequately portrayed by a bottom-up analysis.

When the characteristics of bottom-up models are considered together, the corresponding effect on estimates of emission reductions and total costs of climate

policies can be deduced. Because of the combined effect of assumptions regarding the baseline, the lack of macro-economic feedback, the characterization of costs and the subsequent representation of the rate of technological change, bottom-up models typically result in low estimates of the total cost and high estimates of emission reductions from climate policy.

### *Top-Down*

In comparison, top-down analyses are rooted in aggregate economic modelling, and rely on historical market data to estimate the relationships between the relative costs and market shares of inputs to the economy (including energy). These aggregate relationships are further linked in a broad equilibrium framework to sectoral and total economic output (Weyant, 1998). While top-down models incorporate macro-economic feedback and consumer preferences, they do not include detailed representations of technologies. This lack of technological detail and the resulting way technological change is described in top-down models are the source for many of the criticisms of the top-down approach.

The rate of technological change is determined in top-down models with the use of an exogenously specified index of the autonomous improvements in energy efficiency (AEEI), and price-consumption relationships such as ‘own price elasticities’ and ‘elasticities of substitution’ (ESUB). The AEEI describes the rate at which energy productivity improves as a result of ‘price independent technological evolution’ (Jaccard et al., 2003). ESUB values specify the substitutability between aggregate inputs (capital, labor, energy and materials) and between energy forms. Both the AEEI and ESUB values are estimated from historical market data (Hourcade and Robinson, 1996; Edmonds et al., 2000).

Top-down models typically report much slower technological progress than bottom-up models, and estimate higher costs for more moderate emission reductions. The reason for the high cost estimates relates to assumptions in the baseline as well as how costs are calculated. First, because top-down models assume that the baseline case is

economically efficient (i.e. consumers have made welfare-maximizing decisions), any change induced by policy entails a loss of welfare, or a cost to society (Edmonds et al., 2000). Second, the use of price-consumption relationships to calculate the full costs to consumers of achieving a given emission target inherently includes lost consumers' surplus. Hence, top-down models produce higher cost estimates for emission reductions than bottom-up models.

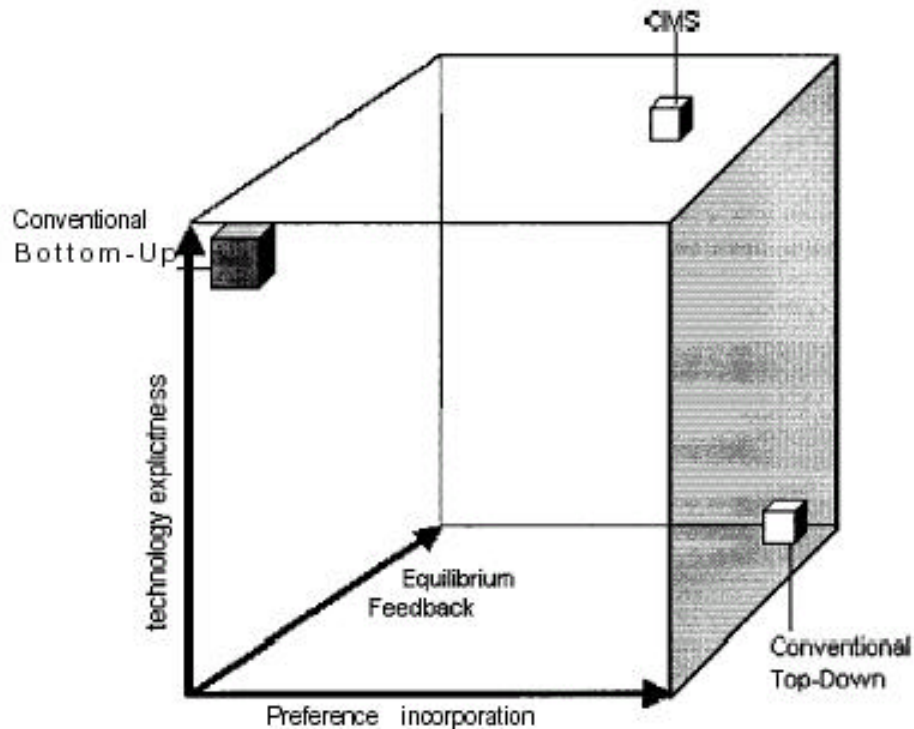
However, the top-down approach is criticized for over-estimating the cost of emission reductions because the historical price-consumption relationship cannot accurately indicate the likely consumer preference for new technologies in the future. Emerging government policies induce development and commercialization of new, more efficient technologies, and associated economies of learning and economies of scale drive down the financial costs of these technologies over time. Correspondingly, the increased market penetration and falling costs of these technologies infer higher AEEI and ESUB values and the ability for GHG emission reductions to be achieved at a lower cost. Consumers' preferences are also likely to change over time, and under the influence of policies, which means less value is lost when consumers switch from one technology to another, resulting in lower estimates of the cost of a policy (Jaccard et al., 2003).

Furthermore, the lack of technological detail and exogenous specification of the AEEI in top-down models precludes the ability to represent potential future technology options and for policies to affect the rate of technological change (Azar and Dowlatabadi, 1999). Because technological change is represented with abstract, aggregate parameters (AEEI, ESUB) top down models are restricted in their application to the evaluation of 'top-level' policy instruments such as taxes. This greatly hinders the usefulness of top-down models for policymakers who may prefer more targeted instruments like subsidies, or technology specific regulations.

To summarize the differences between top-down and bottom-up models, Jaccard et al. (2003) use a 3-dimensional cube (figure 2) with technological explicitness (detail), equilibrium feedbacks, and preference incorporation on the three axes. As discussed,

conventional bottom-up models incorporate considerable technological detail, but do not adequately incorporate consumers' preferences or equilibrium economic feedbacks, placing them in the top-left-front quadrant of the cube. Top-down models fall in the bottom-right-back quadrant of figure 2 because they are strong in equilibrium feedback and preference incorporation, but lack explicit representation of technologies.

**Figure 2. Characterization of energy-economy models**



(from Jaccard et al., 2003)

### *Hybrid*

Energy-economy models that are strong in all three characteristics are most useful to policymakers, and fall in the upper- right-back quadrant of the cube pictured in figure 2. Hybrid models attempt to fill this role by addressing the criticisms of top-down and bottom-up models by acknowledging the importance of, and incorporating, technological detail, consumer preferences, and economic feedback. Analyses using hybrid modelling approaches typically produce estimates of costs and GHG emission reductions that fall in



between bottom-up and top-down analyses of the same problem (Jaccard et al., 2003).

Hybridization has been approached from both the top-down and bottom-up directions. For example, top down models can gain more technological detail by further disaggregating sectors and using more detailed elasticity values. The Second Generation Model (Edmonds et al., 1991) is an example where production sectors were further disaggregated and more disaggregated ESUB values were used, thus gaining greater technology resolution. The level of technological explicitness of the SGM and other top-down hybrid models are still second to that of bottom-up models.

Bottom-up models begin with the benefit of considerable technological detail and can be enhanced with both greater economic and equilibrium feedbacks, and a representation of consumer preferences. The MARKAL model, a bottom-up linear programming model, has been enhanced with economic drivers (e.g. population growth, own price demand elasticities) to improve the economic feedback in the model. However, MARKAL is based on a least-cost approach, which assumes that consumers choose technologies with the lowest financial cost – ignoring consumers’ surplus and option value. MARKAL would then fall in the upper-back quadrant, but towards the left reflecting the lack of realistic preference incorporation.

Bottom-up models may also incorporate consumers’ preferences with the use of information from marketing research and discrete choice modelling studies. CIMS, a bottom-up hybrid model of the Canadian energy-economy, has incorporated economic feedback with the use of energy service elasticities and integrated supply and demand between energy and production sectors. CIMS has also incorporated parameters describing consumers’ preferences informed with the use of discrete choice surveys, as well as revealed and stated preference surveys. Because CIMS includes technological detail, economic feedback as well as a realistic representation of consumers’ preferences it falls farthest to the right in the upper-back quadrant of figure 2.

While this section has focused on the characteristics that make a useful energy-economy model, further characteristics are required in order to produce a model that is

useful in evaluating the effect of climate policies on CAC emissions. These characteristics are discussed in following sections and include the aggregation level of coefficients used to calculate CAC emissions (section 1.5), and the level of geographical detail that the estimated changes are reported with (section 1.7).

## **1.5 Calculating CAC Emissions and the Aggregation Level of Emissions Factors**

Following the chain of analysis outlined in section 1.3, the next step in ancillary effects estimation is to use the estimated changes in fuel demand from an energy-economy model to calculate changes in CAC emissions. Approaches to estimating CAC emission changes vary in terms of how well they include the process parameters that determine CAC emission intensity and the level of detail used to determine these changes. The following paragraphs discuss past approaches to estimating the ancillary effects of climate policy with a focus on the level of detail used in calculating and representing CAC emissions.

The level of aggregation in emission factors applied in different studies is a function of both the nature of the energy-economy model used in the first step of the analysis, as well as the focus and scope of the study in question. When relying on the outputs from a top-down energy-economy model, analysts have little choice but to apply aggregate emission factors, as the output from the model is limited to estimated aggregate changes in fuel demand. Burtraw and Toman (1997) summarize the modeling approaches taken in past studies, with the vast majority being top-down, national scale economic models relying on aggregate fuel based or sector based emission factors. Complainville and Martins (1994) is an exception to this case as they employed a top-down, multi-sector, multi-country dynamic applied general equilibrium model (GREEN) and combined this with emission factors that began as disaggregated factors that were then rolled-up into more aggregated, cross-sector emission factors.

More disaggregated models and hence more specific emission factors have been used in the past, but generally when the scale of the study is smaller, and often focused on regional electricity sectors. For example, Burtraw and Toman (1999) incorporated emission factors specific to the facility level, and also summarize the different models that have been applied to the U.S. electricity sector for the purpose of ancillary effects estimation.

In contrast, all Canadian, national-scale evaluations of the ancillary effects of climate policy published to date have begun with outputs from technology specific, hybrid energy-economy models (EHI, 2000), and then applied aggregate fuel-based emission factors. This approach was also taken by Syri et al. (2001) who used PRIMES, a hybrid, technologically detailed energy model for the European Union and incorporated aggregate, fuel based emissions factors.

Understandably, the reliance on aggregate emission factors is one way to maintain simplicity in a model, and prevent creating an overly complex representation of the system that would make understanding the underlying mechanisms more difficult (Ayres, 1978). However, relying on aggregate emission factors, regardless of what type of energy-economy model is applied, results in the loss of detail required to properly estimate and relate CAC emissions to their sources. As stated in section 1.1.2, CAC emissions vary with different process characteristics such as running temperature, operation and maintenance, or different combustion characteristics (e.g. temperature, duration, maintenance level).

Top-down models do not have the capability to trace technology specific emission contributions, even when emission factors are rolled up from a more detailed level. Technology specific, bottom-up or hybrid models are not restricted by their structure to the use of aggregate emission factors. However, when aggregate rather than technology-specific emission factors are applied to bottom-up estimates of fuel demand changes, the relative contributions of different technologies to the total change in emissions is lost.

The loss of technological detail that results from relying on aggregate emission

factors precludes the use of the model to address a number of policy questions and eliminates a richness of detail that could better help decision makers understand why decreases and increases in CAC emissions can result from climate policies. As mentioned earlier (section 1.4.1), policymakers may prefer to use instruments that target specific technologies (such as regulations). If the emissions cannot be traced through the model to the associated technology, designing and evaluating these targeted policies will be a more difficult and less valuable exercise. This further emphasizes the value of energy-economy models that have a high degree of technological detail (i.e. bottom-up hybrids) in ancillary effects research. When these models are enhanced with equally detailed CAC coefficients the types of policies that can be addressed are more numerous and the richness of the analysis is improved.

## **1.6 Estimating Impact and Valuation of Costs and Benefits**

The final steps in the ancillary effects analysis pathway include estimating changes in ambient air quality, determining the potential environmental and health impacts of these changes, and ultimately monetizing these changes into costs and benefits (steps 4-6 in figure 1). As indicated, each of these steps involves considerable expertise and uncertainty. Estimating the ambient air quality changes requires knowledge of the geographic location of emission sources, the dispersion characteristics of the specific pollutant, regional climate and weather patterns, as well as the existing ambient air quality (Ekins, 1996; Pearce, 2000; Burtraw and Toman, 2001). Translating the changes in ambient air concentration into environmental and human health impacts in turn requires an understanding of local population demographics, the dose-response relationship (for human effects) and an understanding of local ecosystems that could be affected. Finally, in order to determine the extent that ancillary effects alter the net costs or benefits of a climate policy, human and environmental impacts are monetized. Typically, the ancillary effects are reported as a \$/tonne of GHG abated (Burtraw and Toman, 2001).

The final two steps in the analysis are controversial, both in terms of the great uncertainty involved in estimating the dose-response to pollutants, and the valuation of human health effects and environmental damages (Davis et al., 2000). A detailed description of the literature surrounding these steps is beyond the scope of this report, but for a comprehensive review of the issues involved see Davis et al. (2000), Burtraw and Toman (2001), and Cifuentes et al. (2001).

### **1.7 Geographic (Spatial) Disaggregation**

As indicated, in order to accurately estimate the air quality changes and the impact on the environment and humans, the geographic location of emission changes must be known in considerable detail. Davis et al. (2000) and Burtraw and Toman (1998) assert that the estimated benefits or costs associated with changes in CAC emissions will vary greatly depending on the geographic location and proximity to human populations. Thus the estimated change in CAC emissions predicted by energy-economy models will result in more accurate estimates of associated costs and benefits if they are spatially precise.

An example of geographically detailed estimation of the ancillary effects of climate policy is presented by Burtraw and Toman (1999), who use a location-specific, economic model of the electricity sector (named HAIKU). The model produces region-specific emission changes for the five, eastern North America Electricity Reliability Council (NERC) regions in the United States (each NERC region includes a number of states). The emission changes estimated by HAIKU were then fed into an integrated assessment model that determined the change in air quality, environmental and human impacts. A number of other similar studies, specific to the regional scale are outlined in Burtraw et al. (1999).

Canadian attempts at estimating ancillary effects of climate policy, as described in section 1.6, have relied on technologically detailed hybrid models (CIMS, MARKAL) which can produce estimates of GHG emissions that are specific to the sector-region scale (e.g. Ontario electricity sector). However, the sector activities and the related emission

changes may be scattered across the province making it difficult to translate sector/region emission changes into changes in the air quality of a particular airshed.

The ideal level of spatial disaggregation in a model depends on the characteristics of the affected airshed (how big is it, is it split across two regions), and the location of affected populations in the airshed. But analysts must also consider the complexity of the modelling tool. Incorporating better spatial resolution into energy-economy models may greatly increase the data needs and the time it takes the model to calculate results. One compromise is to use a modelling tool that takes the emission changes estimated by an energy-economy model and disaggregates them to a level of finer geographic detail. With this approach the emission changes can be translated to a finer level of spatial resolution without adding cumbersome details to the energy-economy model itself.

## **1.8 Summary of Evaluative Criteria**

Elements of the preceding discussion can be tied together to form a list of evaluative criteria that describe the characteristics of an energy-economy model that would be most useful in evaluating the ancillary effects of climate policy. These criteria include:

- technological explicitness (detail),
- preference incorporation,
- disaggregation of emission coefficients, and
- spatial disaggregation.

Technological detail is needed to support the accurate calculation of CAC emissions, to help understand the source of emission changes and to evaluate a wider range of more technology-specific policy options. Consumers' preferences must be realistically and fully incorporated in the model in order to describe how policies will most likely affect consumer choices and hence the evolution of technologies and emissions over time. Disaggregated emission factors should be used in order to carry the level of

technological detail in the model through to the estimation of CACs. Finally, the level of geographic detail should be sufficient to associate the changes in CAC emissions to the appropriate airshed, and allow a more accurate determination of air quality changes, the subsequent impact on humans and the environment, and the resulting costs and benefits.

## **1.9 Uncertainty in Energy-Economy Modelling**

Each step in the analytical chain to evaluate the ancillary effects of climate policy involves a degree of uncertainty. As asserted by Morgan and Henrion (1990), responsible policy analysts should always strive to characterize the limitations (uncertainties) associated with the ‘answers’ they provide. There are numerous relevant sources of this uncertainty in policy analysis, including: the type of model used to represent the complex relationships involved, the natural variability in the system being described, systematic errors such as bias and imprecision in estimating the parameters in the model, and a lack of information regarding future conditions and changes in parameter values (Morgan and Henrion, 1990). Thus in order to understand the total uncertainty involved in estimating the ancillary effect of climate policies, uncertainty must be characterized at each step in the analytical chain and propagated through to the results. In climate policy analysis in particular, a great deal of time is spent focusing on the uncertainty of climate change impacts, and far less is spent understanding the uncertainty involved in estimating the costs and effectiveness of these policies.

Uncertainty in energy-economy modelling has been examined in a number of ways. Researchers have explored the uncertainty in energy-economy model structure (Manne and Richels, 1994) and the effect of this uncertainty on estimates of the cost of climate policies. Others have explored the effect of uncertainty in GHG emissions factors on the estimated GHG emission changes associated with policies (El-Fadel et al., 2001). However, as asserted by Heal and Kristrom (2002) ‘valuable insights’ remain to be gained by continuing to probe the uncertainty in economic modelling, and in particular the uncertainty associated with key drivers such as consumer preferences and rates of

technological change.

Characterizing the uncertainty in the ancillary effects estimation of climate policy is even less common a practice, yet is equally important in terms of understanding the overall effect of uncertainty on the ancillary costs and benefits of related policy (Davis et al., 2000; Burtraw and Toman, 2001). The uncertainties associated with these latter steps in the analytical chain (namely atmospheric concentration, impact estimation and valuation) are believed to be large but are rarely quantified. Whether the characterization of uncertainty is quantitative or qualitative, some indication of the effect of this uncertainty on the ultimate estimation of costs and emission reductions should be noted (Davis et al., 2000).

### **1.10 Research Objectives**

The preceding paragraphs have established the need for climate policy analyses to consider the ancillary effects on local air pollution. Correspondingly, decision-makers need a way to keep track of how policies crafted to reduce GHGs can also affect the emission of CACs. The most common assumption in the literature is that measures to reduce GHGs will result in CAC reductions. In order to properly test this type of assumption, and to get a clearer idea of the magnitude of CAC emission changes, a tool is required that can track the actions stimulated by GHG policy and the corresponding changes in CAC emissions.

Hence, the objectives of this research project are:

- 1) To develop a Canadian energy-economy model capable of estimating GHG emissions and CAC emissions over time.
- 2) To use this model to evaluate the CAC emission changes associated with policies aimed at reducing GHG emissions.
- 3) To evaluate how well the developed modelling tool meets the outlined criteria for an effective ancillary effects evaluation tool.



Once developed, the proposed modelling tool will fulfill the first half of the analytical chain pictured in figure 1.

In the next chapter the choice and details of the modelling tool are outlined including a discussion of the data sources and the approach to incorporating CAC estimation capacity into the model. Section 3.0 presents the policy analysis, using sector specific examples to highlight some of the synergies and antagonisms between climate policies and CAC emissions, and sensitivity analysis to explore the effect that uncertainty about parameter values and assumptions has on the usefulness of model outputs. Finally, in section 4.0, a summary of the research findings is presented along with suggestions for future research.

## Methodology

The research objectives outlined in section 1.10 were pursued with an established hybrid energy-economy simulation model, already used to estimate the greenhouse gas (GHG) emissions and the costs associated with Canada's climate policy alternatives as part of the National Climate Change Process (NCCP)<sup>3</sup>. The following section (2.1) further describes the rationale for choosing the CIMS model in this research, and then details the structure and function of the model. In section 2.2 the approach taken to incorporating criteria air contaminants (CACs) into CIMS is described along with a discussion of how CAC emissions are calculated, the data sources used, and the challenges involved. In the closing sections the process of calibration is discussed along with a number of assumptions that were made, and the uncertainty surrounding the representation of CACs is discussed.

The preceding chapter established and discussed both how the ancillary costs and benefits of climate policies are calculated, with the focus on the role of energy-economy models forming the first link of this chain. A number of evaluative criteria were outlined and discussed in terms of how an energy-economy model can be most useful in informing climate policy and ancillary effects estimation (section 1.8). The criteria include:

- technological explicitness (detail),
- preference incorporation,
- disaggregated emission coefficients, and
- spatial disaggregation.

As indicated earlier, hybrid models incorporate the first two criteria, by bridging gaps between top-down and bottom-up approaches. The hybrid simulation model, CIMS, is a Canadian example of an energy-economy model that has been used in the past to evaluate climate policies, and provides a relatively disaggregated representation of

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<sup>3</sup> See the report entitled "Integration of GHG Emission Reduction Options Using CIMS" by MKJA (2000) for a synthesis of the work done for the National Climate Change Process.

emissions changes to the sector-region level. The third criterion informed how CAC emissions were incorporated into the model, which is discussed in section 2.2. The fourth criterion is the most challenging for CIMS, as it is not a spatial model and may not on its own provide enough detailed information describing where emissions and emission reductions occur. Whether or not the sector-region emission estimates of CIMS are sufficient to inform the evaluation of ancillary costs and benefits will be further addressed in section 3.2.3 of the analysis.

## **2.1 Introduction to CIMS**

CIMS is a simulation model, developed by the Energy and Materials Research Group at Simon Fraser University, which was designed to help policy makers understand the effect of policy alternatives aimed at changing energy demand and emissions. Sometimes characterized as a hybrid model, CIMS addresses the criticisms of bottom-up and top-down models (as discussed in section 1.4) by incorporating both technological detail and consumer preferences. CIMS also provides geographically disaggregated estimates of emission changes, to the level of region-sector (e.g. Ontario electricity sector). In combination with the representation of the energy system, and capacity to estimate GHG emission, these characteristics made CIMS the ideal tool to enhance with the capacity to estimate associated changes in CACs.

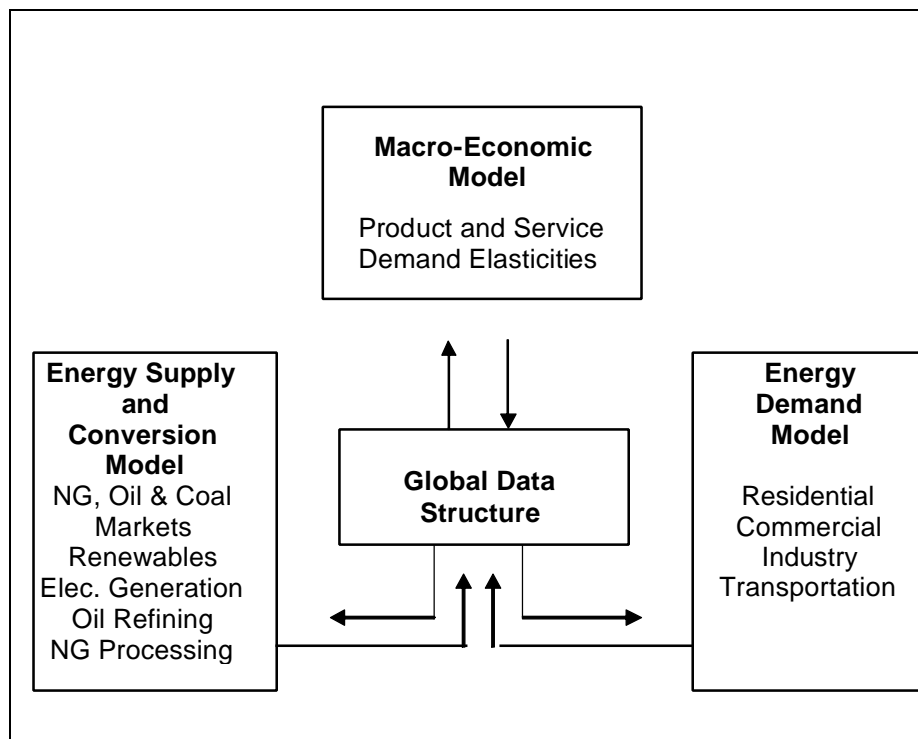
### **2.1.1 Structure and Function**

CIMS represents the economy in terms of annual energy services. Energy services are as diverse as tonnes of market pulp produced, person-kilometers travelled, and square meters of heated commercial floor space. The alternative technologies for providing each service are characterized in terms of capital cost, operating costs, energy costs, energy efficiency, fuel type, lifespan, date of first availability, and intangible costs related to consumers' surplus. Other decision parameters include discount rates, dependence on related investment decisions, constraints on market penetration and cost-reducing

feedbacks related to levels of market penetration.

As illustrated in figure 3, CIMS has three major components. The energy service demand component includes the residential, commercial / institutional, industrial and transportation sectors. The energy supply component includes conversion models of electricity generation, petroleum refining and natural gas processing alongside supply curves for fossil fuels and renewables. The macro-economic component includes energy service elasticity parameters that relate product and energy service demands to their costs. Note that for this study, the macro-economic feedback loop was disabled to permit the isolation of the direct emission reductions associated with policy alternatives.

**Figure 3. The major components of CIMS**

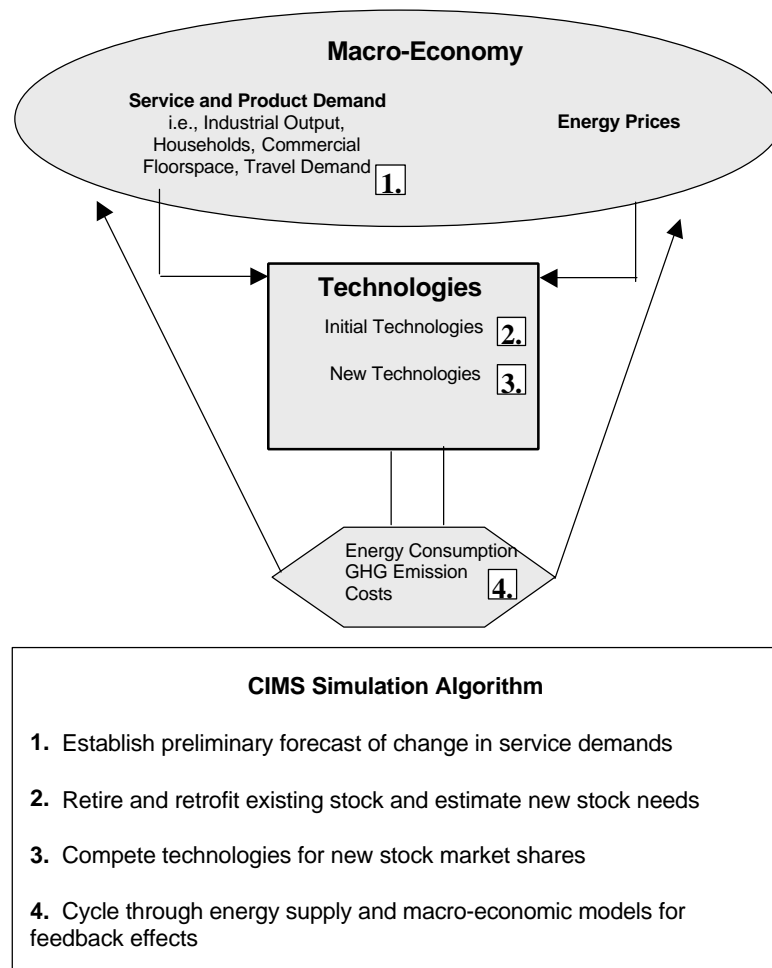


CIMS covers the entire Canadian economy and currently models six individual provinces and an aggregation of the Atlantic Provinces (Table 1 in Appendix B lists the sectors and regions included in the CIMS database).

### 2.1.2 Simulation Process

For this project, a CIMS simulation involves four basic steps (as illustrated in figure 4). First, energy service demand is forecasted in five-year increments (e.g., 2000, 2005, 2010, 2015, etc.).

Figure 4. Basic steps in a CIMS simulation



(from p.58 Jaccard et al., 2002)

In each future period, a portion of initial-year equipment stocks is retired, following a time-dependent function. The remaining technology stocks are tested to see if retrofitting is desirable given the economic conditions and service demands (step 2).<sup>4</sup>

If new stocks are required because of the combined effect of equipment retirement and growing service demands, prospective technologies compete to determine which will contribute the remainder of the energy services (step 3). Technologies are allocated market share using a probabilistic function of life-cycle costs, including intangible preference related costs. Section 2.1.3 presents a detailed description of how market share is determined. Next the model iterates between energy demand and energy supply components until energy prices stabilise at equilibrium (step 4). The previous steps are started again in the next time period with an energy forecast demand that reflects the new conditions.

Since each technology has an associated net energy use, net emissions and costs, the simulation ends with a summing of these. The difference between a business-as-usual simulation and a policy simulation provides an estimate of the emission changes and cost of a given policy or package of policies.

### **2.1.3 Determination of Market Share**

The equations that determine the proportion of new market share that a technology will capture are described below. In equation 2, the market share function ( $MS_{kt}$ ) is a logistic relationship between the life-cycle cost of a given technology and all other technologies that compete to fulfill the same service demand.

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<sup>4</sup> Retrofit options are characterized with the same financial and non-financial information as normal technologies, except that the capital costs of residual technology stocks are excluded, having been spent earlier when the residual technology stock was originally acquired.

**Equation 2**

$$MS_{kt} = \frac{LCC_{kt}^{-\nu}}{\sum_{k=1}^z LCC_{kt}^{-\nu}}$$

where:

- $MS_{kt}$  = market share of technology  $k$  for new equipment stocks at time  $t$ ,  
 $LCC_{kt}$  = annual life cycle cost of technology  $k$  at time  $t$ ,  
 $\nu$  = variance parameter,  
 $z$  = total number of technologies competing to meet service demand.

The slope of the logistic curve is determined by the value of  $\nu$ ; the magnitude of  $\nu$  describes the relationship between life-cycle costs and market share for different technologies. A high value for  $\nu$  (e.g. 100) implies that the lowest life-cycle cost technology will capture the entire market share. In comparison, a very low value for  $\nu$  (ex.  $\nu = 1$ ) results in the market share being distributed evenly amongst competing technologies, regardless of their life-cycle costs.

The life-cycle cost for a specific technology is calculated using the following formula (equation 3).

**Equation 3**

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

where:

- $CC_{kt}$  = capital cost of technology  $k$  at time  $t$ ,  
 $SO_k$  = annual service output of technology  $k$ ,  
 $O_{kt}$  = operating cost of technology  $k$  at time  $t$  per unit of service output,  
 $E_{kt}$  = energy cost of technology  $k$  at time  $t$  per unit of service output,  
 $r$  = discount rate (time preference)  
 $n$  = equipment lifespan

Equation 3 calculates the life-cycle cost ( $LCC$ ) as a function of annualized capital costs, operating, and energy costs. The discount rate ( $r$ ), determines the relative importance of capital costs versus operating costs in the total life-cycle cost of a technology. A higher discount rate places greater weighting on capital costs and results in a high LCC, while a lower discount rate will produce a lower LCC, given equal operating and energy costs. Hence, a high discount rate will hinder the ability of technologies with high capital costs and lower operating and energy costs to gain market share (competitive disadvantage). Because new, energy efficient technologies often have a high capital to operating cost ratio, a high discount rate will impede the market penetration of these technologies (Nyboer, 1997).

Capital costs are calculated using equation 4, which incorporates both financial and non-financial, or intangible costs:

**Equation 4**

$$CC_{kt} = FC_{kt}(1 + i_{kt})$$

where:

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

The intangible cost factor ( $i_{kt}$ ) is a value between 0 and 1 that serves as a multiplier, increasing the capital cost beyond simply the financial cost of a technology to reflect one or several factors such as identified differences in non-financial preferences (differences in the quality of lighting from different light bulbs) and perceived risks (one technology is seen as more likely to fail than another) of technologies (Jaccard et al., 2003).

A more detailed description of the CIMS simulation procedure, equilibrium algorithm, and inputs is available in Nyboer (1997) or can be obtained by contacting the author.



## 2.2 Incorporating Criteria Air Contaminants

The CACs incorporated into CIMS for this study include sulphur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), volatile organic compounds (VOC), carbon monoxide (CO), and particulate matter (PM). Where possible (i.e. where data was available), particulate matter is further characterized by size, where PM<sub>10</sub> is particulate matter less than 10 microns in diameter, and PM<sub>2.5</sub> has a diameter less than 2.5 microns.

As indicated in the previous section, emissions are calculated at the end of each time period once the supply and demand models have stabilized at equilibrium. Emission information is summarized in CIMS with the use of emission factors (EFs). Fuel related emission factors ( $EF_f$ ) are coefficients that indicate the amount of a specific emission generated per GJ of a given fuel demanded. Fuel related emission factors are multiplied by fuel demand coefficients (GJ / unit output) and then by the total material or service output of the specified technology in order to arrive at total emissions generated for the technology. Process related emission factors ( $EF_p$ ) relate the emissions generated to the service demand, material output or input to a technology or process, and are usually in units of tonnes of pollutant per unit output, input or service. Equations 5 and 6 are a generalized sample of the formulas used to calculate fuel-related and process-related CAC emissions from a technology.

### Equation 5. Fuel combustion emissions

$$\text{Kg of pollutant generated} = EF_f \times FC \times O$$

where:

|        |   |   |
|--------|---|---|
| $EF_f$ | = | fuel-combustion emission factor (kg pollutant / GJ energy demanded)                 |
| $FC$   | = | fuel coefficient (GJ energy demanded / unit output)                                 |
| $O$    | = | unit of output (ex. tonnes pulp, m <sup>2</sup> floor space heated or cooled, etc.) |

**Equation 6. Process related emissions**

$$\text{Kg of pollutant generated} = EF_p \times O$$

where:

- $EF_p$  = process related emission factor (kg pollutant / unit output)  
 $O$  = unit of output (ex. tonnes pulp, m2 floor space heated or cooled, etc.)

**2.2.1 Fuel-related Emissions**

As indicated in equation 5, each specific fuel (natural gas, heavy fuel oil, etc.) has a unique emission factor for each associated pollutant (NO<sub>x</sub>, SO<sub>x</sub>, etc.). Some  $EF_f$ 's are further differentiated by sector; For example, industrial combustion of coal has a different emission factor for SO<sub>x</sub> than combustion of coal by an electricity generating utility. Table 1 presents the general disaggregation of the fuel-related emission factors by fuel-type, emission, and sector. The letters (A, B, C) represent individual fuels, while the numbers (1, 2...) represent the different emissions. The actual fuel related emission factors used in the model are presented in Appendix B, table 1.

**Table 1. Fuel combustion-related emission factors**

| Emission Type | Units   | Industry               |                        |                        | Transportation         |                        |                        |
|---------------|---------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
|               |         | A                      | B                      | C                      | A                      | B                      | C                      |
| 1             | Kg / GJ | Ef <sub>f (1, A)</sub> | Ef <sub>f (1, B)</sub> | Ef <sub>f (1, C)</sub> | Ef <sub>f (1, A)</sub> | Ef <sub>f (1, B)</sub> | Ef <sub>f (1, C)</sub> |
| 2             | Kg / GJ | Ef <sub>f (2, A)</sub> | Ef <sub>f (2, B)</sub> | Ef <sub>f (2, C)</sub> | Ef <sub>f (2, A)</sub> | Ef <sub>f (2, B)</sub> | Ef <sub>f (2, C)</sub> |
| Etc...        |         | ...                    |                        |                        | ...                    |                        | ...                    |

(where A, B... = fuels, 1, 2...= pollutants)

### **2.2.2 Process-related Emissions**

As indicated in equation 6, process-related emission factors relate the amount of emissions generated to the material throughput or service demand met by a technology; however, these emission factors are not always exclusive of emissions resulting from fuel combustion. Because emission factors are developed by measuring the emissions that are released at some identified end point of a technology process it is difficult to discern which portion of measured emissions are directly related to fuel combustion and which are related to the process materials or characteristics (e.g. rotary kiln where combustion gases and process materials mix). Hence, process-related emission factors are used to characterize emissions in the following situations:

- The emission production is related to both the combustion of a fuel, the material components of a process and the incremental effect of each cannot be separated.
- The emission production is process dependent, and a small change in some aspect of the process can affect the amount of emissions generated.

Finally, process-related emission factors are truly technology specific, and permit the representation of greater heterogeneity in emission production than fuel-related emission factors.

### **2.2.3 Data**

In order to incorporate CACs into CIMS, technology specific emission factors relating the amount of a pollutant generated to the energy and/or service level of a technology were used. However, due to a lack of sufficiently detailed Canadian data, the majority of the CAC emission data used in this study is adapted from the U.S. Environmental Protection Agency AP-42 and FIRE 6.23 databases of emission factors. The AP-42 databases are public and peer reviewed, and the most recent version available (5<sup>th</sup> Edition) was consulted for this study.

The emission factors in the AP-42 / FIRE 6.23 are technology specific, and in general are averages of all available data that describe the relationship of activity to emissions with acceptable quality. CIMS characterizes technologies as averages (i.e. a technology has the same capital cost and unit energy demand whether it is in B.C. or Ontario), and this characterization is consistent across regions. Thus, AP-42 emission factors are well suited to characterize CAC emissions in CIMS.

Considerable effort was spent matching the technologies in the AP-42 with those in CIMS. Using AP-42 EFs for Canadian technologies requires the assumption that Canadian and U.S. technologies are comparable. However, not all CIMS technologies were described by a matching AP-42 technology. When no exact match was available, a number of alternatives were pursued:

- 1) If the CIMS technology represented an aggregation of a number of AP-42 technologies, the EFs were combined (in most cases added together) and assumed to represent the CIMS technology.
- 2) If no exact match for a technology was found in the AP-42 but there was a CIMS technology with similar characteristics, the AP-42 EFs for that technology were used.
- 3) If a match was found and the AP-42 indicated that a specific emission was produced however insufficient data existed to develop an emission factor, either the EFs from a similar technology in CIMS were applied, the EF was derived from another data source, or the EF was omitted.

### *Fugitive Emissions*

Fugitive emissions occur as leaks from process equipment or evaporate from open areas, and are not captured at the stack or vent where emissions are typically measured for a technology (EPA, 1995a). In some cases, fugitive emissions such as leaks from valves or seals can be directly attributed to a technology, in which case they are added to the

process emission factor for that technology.

NO<sub>x</sub> and VOC fugitive emissions are of particular importance in the natural gas processing and petroleum refining sectors. In the natural gas sector, actions are represented in lieu of specific technologies. An action in this case refers to an alternative way of fulfilling the service output, whether through conventional technologies, or with small process changes such as increased maintenance or feedback looping. No match for the ‘actions’ were available in the AP-42 data source. However, using guidelines from the U.S. EPA ‘Protocol for Equipment Leak Emission Estimates’ (1995b), approximate fugitive EFs were developed and applied to specific actions, with adjustments for actions that would impact the emission level.

The dust (particulate matter) that arises when materials are mechanically disturbed does not travel in a discrete flow stream and cannot easily be measured, is also referred to as ‘fugitive’. As with fugitive VOC emissions, these emissions have been associated with relevant existing CIMS technologies, and the emission factor added to the PM emissions for that technology. Note, however, that the dust generated from transportation (i.e. driving on gravel or dirt roads) is not included in calculations of fugitive particulate emissions.

### *Transportation Data*

Emission factors for the transportation sector relate emissions to vehicle-kilometers-travelled (vkt). Most transportation emission factors used in CIMS were adapted from the “On Road Emissions Inventory for Canada” (SENES and AIR, 2001) report to Environment Canada for on-road vehicles. Emission factors for non-road vehicles were derived using the RDIS-II inventory and vkt estimates from the 1995 base year in CIMS.

The SENES report predicts emissions of CACs from on-road vehicles over time using vkt growth factors. In comparison, CIMS specifically determines the change in vkt for each transportation mode and vehicle type as part of the competition algorithm.

Furthermore, the SENES inventory includes the effect of the Sulphur Content of Fuels regulation (Regulation No. 361, *Canadian Environmental Protection Act, 1999*), Tier 1 vehicles and National Low Emission Vehicles starting in 2001, as well as 1998 national standards to control NO<sub>x</sub> emissions from heavy-duty gasoline vehicles. All of these regulations and standards will affect the way CAC emissions change over time; therefore, technology specifications and emission factors were adjusted in CIMS to approximate the effect of these standards on CAC emissions over time. In doing so, the transportation emissions are calibrated to the SENES inventory over time.

Finally, only vehicle types already included in CIMS were included in the analysis (therefore motorcycles were not modelled).

### *Other Model Inputs*

Some AP-42 emission factors require additional input in order to more accurately calculate their value. Specifically, to estimate SO<sub>x</sub> and PM emissions produced by fuel combustion an estimate of the percent of sulphur by weight for the specific fuel is required. For liquid fuels this information was taken as the national average sulphur content presented in the Environment Canada (2001) report “Sulphur in Liquid Fuels 1995-1999” (See Appendix B Table 2 for the exact values used). The average sulphur and ash content (required to calculate particulate emissions) of the different types of coal were estimated from information provided by the Canadian Coal Association (also summarized in Appendix B Table 2).

### *Data Quality*

This research project represents the first attempt at using a technology specific, hybrid, energy-economy simulation model to estimate CAC emissions in Canada. Consequently, there are some areas of weakness in the data that stem from the fact that sufficient data from Canadian sources was not available, and necessary assumptions had to be made.

In general, the fuel combustion emission factors (EFs) are the most reliable as fuel

combustion processes do not vary greatly between Canada and the U.S.. The process emission factors, in large part because they are so specific to material use and technology specifications, may vary greatly between Canada and the U.S. and are less reliable.

The sectors with the most data deficiencies include: chemical products, natural gas extraction, and “other manufacturing”<sup>5</sup>. Chemical products and “other manufacturing” are two industrial sub-sectors that have considerable process and fugitive emissions of VOCs, NO<sub>x</sub>, and PM. However, information was not found that would enable the development of EFs for the chemical industry. For the “other manufacturing” sub-sector, the nature of aggregation in the CIMS model precluded the use of more disaggregated EFs from the AP-42 database. The natural gas extraction and transmission industry is not represented in CIMS as technologies, but rather is described as distinct possible actions (as described earlier) with consequent related changes in fuel demand and volumes of natural gas transferred. Each action implies some change in CAC emissions, where the change in emissions could not be related to a change in fuel consumption (i.e. in compressors, etc.) best judgment supported by engineering knowledge and relationships contained in the U.S. EPA (1995b) AP-42 document “Protocols for Equipment Leak Emission Estimates” were used to derive estimates in emission changes associated with the actions represented.

### *Abatement Technology Representation*

CAC emissions are often controlled with the use of abatement technologies; however, there is no explicit representation of separate pollution abatement technologies such as venturi scrubbers, electrostatic precipitators, and baghouses in the model. Because the focus of this research project is on the CAC effects of GHG focused policies, the explicit inclusion of control technologies was not necessary.

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<sup>5</sup> “Other manufacturing” includes smaller industries that do not consume enough energy to fit into their own, larger sub-sector classification in the model, and includes activities such as rubber manufacturing, food and beverage production, and wood products manufacturing.

To represent the effect of pollution control technologies without adding them individually to the model, emission factors for various combinations of control technologies were tracked and applied to technologies where the regional context was deemed appropriate. For example, if B.C. cement manufacturers are known to use electrostatic precipitators to control particulate emissions from lime kilns, a lower, representative emission factor from the AP-42 database was applied. This approach ensures that the likely presence of abatement technologies and the effect on CAC emissions is represented in the model, without the complication of adding the individual technologies along with their detailed characteristics (capital cost, operating cost, energy requirements, control efficiency etc.). Including a detailed representation of individual CAC abatement technologies would be a useful future extension to this research as it would create the potential to evaluate the effect of policies targeted explicitly at CAC emissions with the model.

### **2.3 Calibration**

Calibration is the process of evaluating model outputs against an established, external source or inventory and adjusting model parameters to ensure that the estimated baseline approximates the external estimates. The process of calibration is used both to refine the model, but also to ensure that the results can be compared to results from other similar modeling exercises. As part of the work of MK Jaccard and Associates (MKJA) using CIMS to evaluate climate policy alternatives for the National Climate Change Process, the energy demand and GHG emissions in the reference case were calibrated to ‘Canada’s Emissions Outlook: An Update’ for 1999 (Analysis and Modelling Group, 1999). Fuel demand was calibrated to within 5% and GHG emissions to within 10%.

CAC emissions in the baseline were calibrated to Environment Canada’s Residual



Discharge Inventory System (RDIS-II) for 1995. (An exception is on-road vehicles in the transportation sector which were calibrated to the SENES inventory of CACs over time, see section 2.2.3). This calibration ensured that the emissions estimated by CIMS for the base year (1995) approximate the values developed by Environment Canada which have been vetted through the provinces and stakeholders. A margin of error of  $\pm 25\%$  was allowed. An initial goal of calibrating to within 10% proved to be unrealistic as the two different methods (RDIS-II vs. CIMS) incorporate different assumptions regarding sector level activity and overall fuel use. Also, CAC emissions were not calibrated to future years because at the time of this report there was no consensus between the government and stakeholders regarding forecasted estimates of CACs over time.

CAC calibration was achieved on a specific sector/region basis by following a number of steps. If the pollutant emissions estimated were determined to differ by more than 25%:

- a) The potential for CAC emission control via abatement technologies was evaluated. If emission factors were available and control was likely, these lower values were applied.
- b) If control emission factors were not available, scaling factors were applied. These scaling factors were also used to represent potential differences in material content (ex. sulphur content of lime) and the corresponding effect on emissions.

Appendix C presents the calibration achieved for each sector in Ontario<sup>6</sup>. An indication of the magnitude of scaling factors required for calibration is included.

Calibration was a challenging step of the research, particularly because the assumptions included in the RDIS-II inventory were not available to be compared to those included in CIMS. For example, the CAC emission estimates in the RDIS-II and CIMS are based on production levels, fuel consumption, fuel efficiencies, and process characteristics. Slight differences between any or all of these aspects could result in

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<sup>6</sup> Calibration tables for the remaining regions and sectors can be obtained by contacting the author.

diverging estimates of CAC emissions from CIMS and RDIS-II. Without access to the associated RDIS-II assumptions, the changes made to calibrate the 1995 estimates of

CAC emissions from CIMS were in some cases arbitrary. A better comparison of the assumptions in the two models may provide additional clarity and improve the calibration.

Finally, the RDIS-II inventory records emissions from some sector/regions that are not included in CIMS, therefore only sector/regions included in CIMS were modeled. For example, the RDIS-II includes emissions from a variety of open sources (e.g. agriculture, forest fires, and structural fires) which are not included in CIMS.

## **2.4 Uncertainty**

As discussed in section 1.9, in modelling work of this nature uncertainty is always a factor. The different types of models, the variables and the number of assumptions made regarding their value, all point to the fact that the estimated results reported are within a range of possible values. Uncertainty is further exacerbated by the fact that this is a first attempt at technology specific analysis of this kind in Canada, and that the assumptions of CIMS and RDIS-II could not be compared.

In order to facilitate the characterization of uncertainty involved in estimating CAC emissions a qualitative record of uncertainty for the data used from the AP-42 was established. Table 2 lists each of the indicators and their meaning, ranging from a value of 'A' for quite certain, to 'E' for very uncertain, and incorporate aspects of variability, bias and representativeness. This information can be used to examine the effect of uncertainty in emission factor data on the estimated changes in emissions.

**Table 2. Uncertainty or quality indicators for U.S. EPA emission factors**

| <b>Emission Factor Rating</b> | <b>Meaning</b>  |
|-------------------------------|---|
| A (Excellent)                 | Factor is developed from validated source test data taken from randomly chosen facilities in the industry population. The source category population is sufficiently specific to minimize variability. Bias is low.   |
| B (Above average)             | Factor is developed from well and sufficiently validated test data from a "reasonable number" of facilities. While no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. The source category population is sufficiently specific to minimize variability.  |
| C (Average)                   | Factor is developed either using unproven methodology or lacking background information, using test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. The source category population is sufficiently specific to minimize variability.             |
| D (Below average)             | Factor is developed as per the C rating; however, there also may be evidence of variability within the source population. Bias may be high.   |
| E (Poor)                      | Factor is developed as per the C-rating and the method may be deemed unacceptable, but provides an order of magnitude estimation of the emissions from the source. There may be reason to suspect that the facilities tested do not represent a random sample of the industry, and/or there may be variability within the source category population. Bias may be high. |

Adapted from (U.S. EPA, 1995a)

Note that the uncertainty associated with an emission factors increases when they are applied to the Canadian system described in CIMS because of the additional uncertainty when U.S. determined values are assumed to represent the emissions from Canadian technologies.

Furthermore, previous research has determined that the parameters  $i$ ,  $v$ , and  $r$  which factor into the determination of life cycle costs and thus technology choices (as described in section 2.1.3) are important to the costs and emissions changes calculated. The model results are sensitive to changes in these parameters, which are also quite uncertain. Sensitivity analysis of all three of these parameters should be conducted.

## **2.5 Estimating the Cost of a Policy**

One of the key results from a policy simulation in CIMS is an estimate of the costs associated with different policy alternatives. A previous research project by MKJA (2002) discusses the method of estimating costs of GHG policies with CIMS and provides comprehensive details of cost estimates for a range of shadow prices in each of the regions and sectors included in CIMS.

This chapter has presented how the capacity to estimate CAC emission changes associated with climate policies was built into the CIMS model, satisfying the first research objective. The next chapter addresses the second research objective by applying the model to a specific climate policy analysis, and extracting information regarding the effect of GHG-reducing actions on CAC emissions. The ability of the model to provide spatially disaggregated results will also be explored, addressing the third and final research objective.

## Analysis

As stated in the research objective (section 1.10), the purpose of adding CAC emissions to CIMS is to track and understand the relationship between the GHG-reducing actions stimulated by climate policy, and the corresponding effect on CAC emissions. Thus, the analysis has been designed to focus on determining where synergies and antagonisms exist, the effect on regional CAC emissions, and the ramifications for policy.

Synergies occur when GHG policies stimulate actions that simultaneously reduce GHGs and CACs, while antagonisms are when these actions cause an increase in CAC emissions. A third effect is a neutral response, when very little change in CACs occurs in response to GHG-reducing actions. Antagonisms are of particular concern when considering the effect of climate policies on local air pollution in densely populated urban areas. Understanding the nature of antagonistic increases in CAC emissions can help policy makers explore and design strategies to convert these trade-offs between GHG targeted policies and CAC emissions into synergies.

Three different shadow prices (\$10, \$30, and \$50 / tonne GHG) were evaluated for their effect on GHG emissions, and the associated changes in CAC emissions<sup>7</sup>. Shadow prices are marginal cost signals that approximate the effect of a tax or permit price on emissions. The shadow prices chosen reflect the current consensus in Canada regarding potential prices of domestically traded GHG permits, one mechanism that may be used to pursue Kyoto targeted emission reductions (Government of Canada, 2002). In each shadow price simulation (or policy scenario), the effect of the shadow price is first felt in 2001. Each policy scenario is compared to a business-as-usual (BAU) scenario, and the difference in costs and emissions between the two reflects the effect of the shadow price.

The discussion below begins with a closer look at one specific region that

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<sup>7</sup> For a detailed representation and discussion of the costs associated with these policy scenarios please refer to “Construction and Analysis of Sectoral, Regional, and National Cost Curves of GHG Abatement in

experiences serious local air pollution problems – Ontario, and in particular the Windsor-Quebec Corridor. The overall trend in GHG and CAC emissions in the BAU and the changes that are estimated in the policy scenarios are discussed. Particular attention is paid to understanding where key synergies and antagonisms occur, and the consequence they have on total regional emissions. Next the Alberta electricity sector is discussed because it highlights the interesting potential for large synergies, and a curious antagonistic reaction. Finally, the related assumptions and corresponding uncertainty in the analysis will be elaborated on for two examples, along with a discussion of the implications for interpreting the results and suggestions for further reducing uncertainty in the data.

### **3.1 Summary of Potential GHG Actions**

In response to a GHG shadow price, a number of GHG-reducing actions can occur. Decision makers may choose to: improve the efficiency of their technology stock (either through retrofitting, or by investing in a new, more efficient technology), switch to a different fuel source that is less GHG-intensive, rely more on renewable or alternative energy sources, or reduce output. These actions occur as consumers react to the changing annualized life cycle costs (as described in section 2) of technology options, as stimulated by the shadow price. Hence an inefficient technology that burns coal may become less ‘cost-effective’ with the added effect of a shadow price on the calculation of its life-cycle cost. Therefore, less GHG-intensive alternatives that may have previously been seen as cost-prohibitive will begin to penetrate, resulting in lower GHG emissions.

In situations where a change in technology results in improved energy efficiency associated with carbon-based fuels, there is a synergistic reduction of both GHGs and CAC emissions because less fuel is being used to generate a given service output. But, when fuel switching occurs, a synergy or antagonism may result depending on the relative

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Canada” (MKJA, 2002).

CAC and GHG-intensity of the different fuels. For example, if demand for coal (GHG and CAC-intensive) falls and is replaced with natural gas (less GHG and CAC-intensive) both GHGs and CACs will be reduced. In contrast, if the fuel switch is from natural gas (which has a moderate level of associated GHG emissions) to biomass (a CAC-intensive fuel which is considered a GHG-neutral fuel in the model), a large increase in CACs may result.

In the following section, actions induced by GHG shadow prices in the policy simulations are separated out for illustrative purposes. However, it should be noted that due to the integrated nature of the model a policy will stimulate a number of actions in the economy, which in turn may have a positive feedback effect, stimulating further actions. For example, an action that increases the demand for electricity may increase the price of electricity which will affect the relative desirability of further actions that might involve further increases in electricity demand. Thus, the total change in emissions and costs associated with a policy alternative is a result of a series, or package, of actions and the nature and relative effect of these actions on the penetration of different technologies will determine the magnitude of change in emissions.

In summary, the total effect that a policy has on the emissions seen in a sector/region will depend on the total package of actions that occur. An increase in CACs will be seen when antagonistic actions outweigh the synergistic actions and vice-versa. Further complicating the matter is the fact that an action may cause a synergistic reduction in one or some of the CAC pollutants, but not all. The same can be said for antagonistic increases in CACs. Therefore, the synergies and antagonisms pointed out in the following sections are specific cases where the response was clear and of considerable magnitude.



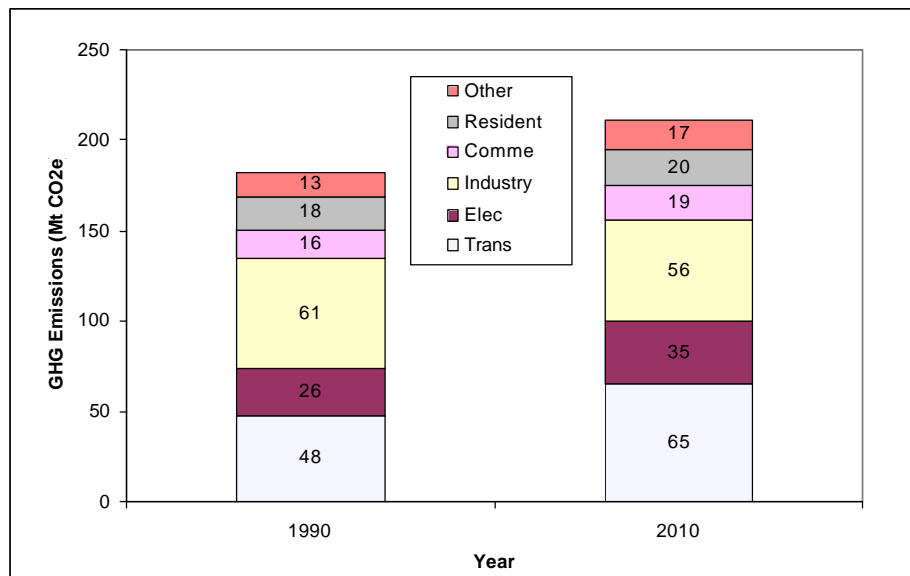
### 3.2 Ontario

Ontario is a large province in terms of geographic size, population size and GHG emissions, and currently emits more GHGs than any other province (Jaccard et al., 2002). The densely populated southeastern region of the province suffers from poor air quality which is exacerbated in the summer months as sunlight interacts with ozone precursors (primarily NO<sub>x</sub> and VOCs) to form photochemical smog (Environment Canada, 2002). The impacts from local air pollution in this region are severe, costing Ontarians \$1 billion<sup>8</sup> a year as a result of increased mortality and morbidity (Environment Canada, 2002). Clearly, the effect of climate policy on CAC emissions in Ontario is an important issue.

#### 3.2.1 The Business as Usual Case

In the business as usual or BAU case, which is based on *Canada's Emission Outlook: An Update* produced by Natural Resources Canada (AMG, 1999), the sectors that contribute the greatest amount to total GHG emissions in Ontario are industry (61 Mt), transportation (48 Mt), and electricity (26 Mt) (see figure 5).

**Figure 5. Ontario Business as Usual Case GHG Emissions by Sector in 1990 and 2010**



(modified from Jaccard et al., 2002)

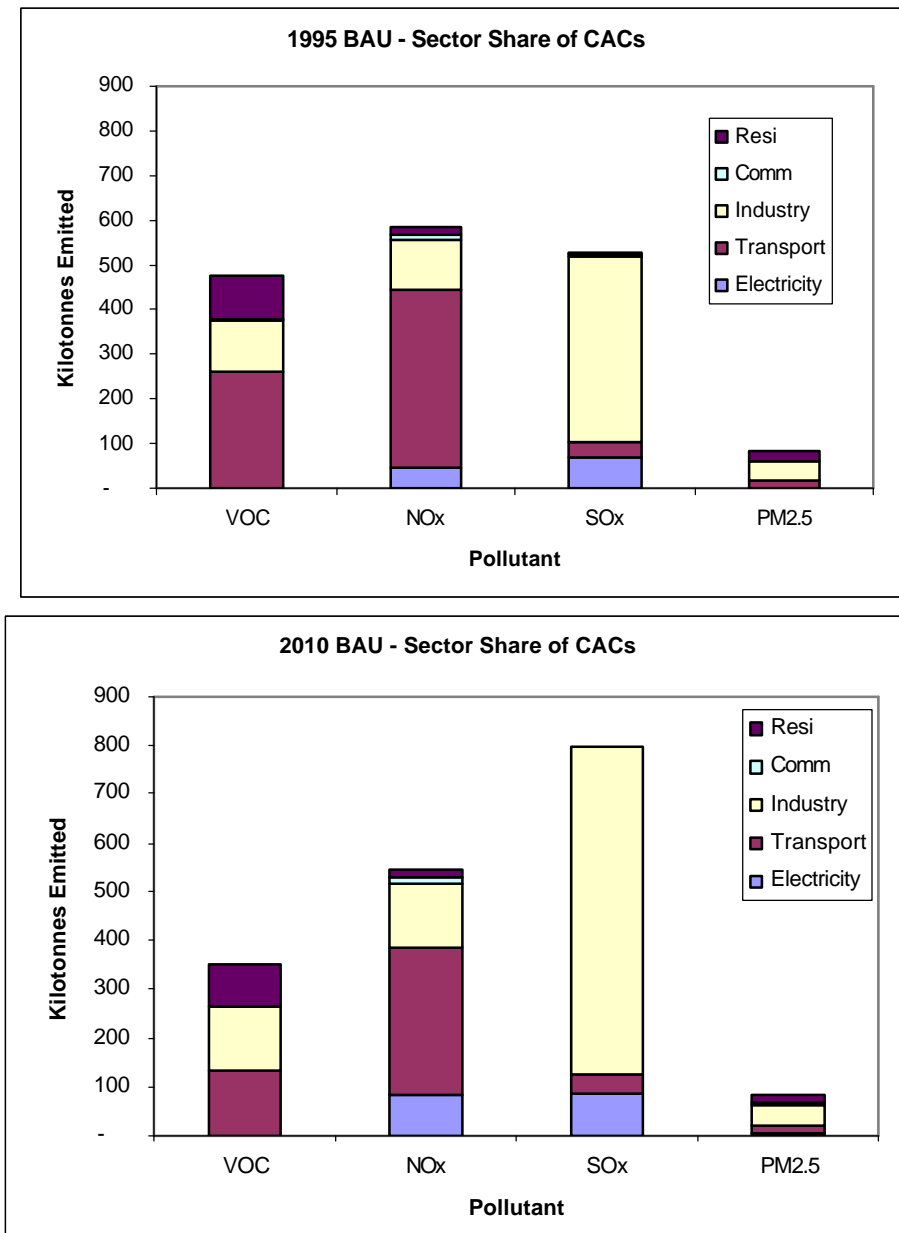
In the reference case established by Natural Resources Canada these proportions are predicted to remain relatively similar by 2010, with reduced emissions from industry as a result of weak or moderate growth in GHG-intensive industries as well as deliberate voluntary actions by a few companies in particular (AMG, 1999). Emissions from electricity rise by 36% between 1990 and 2010 due to increasing demand from a growing population and reduced reliance on nuclear power, which is replaced by thermal sources such as coal. Coal is a GHG-intensive fuel, whereas nuclear power is GHG-benign (Jaccard, 2002).

The relative contribution of different sectors to total CAC emissions is similar, and is illustrated in figure 6. Transportation and industry produce the most VOC and NO<sub>x</sub> emissions, while the majority of SO<sub>x</sub> emissions come from industry and the electricity generation sector. The residential sector contributes significantly to PM<sub>2.5</sub> and VOC emissions which are produced mostly by wood-burning used to supplement home heating.

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<sup>8</sup> Estimate is based on health care costs.

**Figure 6. Sector share of BAU CAC emissions in 1995 and 2010.**



By 2010, all but SO<sub>x</sub> emissions are predicted to decline. The decline in VOC and NO<sub>x</sub> emissions is driven by the transportation sector, and the effect of vehicle fleet turnover (newer, more efficient vehicles) and the sulphur content of fuels regulation. Reductions in PM<sub>2.5</sub> emissions occur mainly in the residential sector as the demand for oil in space heating falls, replaced with more natural gas and electricity technologies.

The marked increase in SO<sub>x</sub> emissions by 2010 is predominantly due to the industrial sector, with contributions from electricity generation as well. In electricity, the increase in SO<sub>x</sub> emissions is related to the increased prevalence of coal-fired generation. The sub-sector that contributes the most to growth in industrial SO<sub>x</sub> emissions is metal smelting and refining, which depends on a number of SO<sub>x</sub>-intensive process technologies.

### 3.2.2 Scenario Analysis

The total emission changes for Ontario in each of the policy scenarios as compared to the business-as-usual (BAU) case in 2010 are presented in table 3. Note that while GHG emission reductions are greater at higher shadow prices, CAC reductions do not follow a consistent trend.

**Table 3. Emission changes in Ontario, 2010**

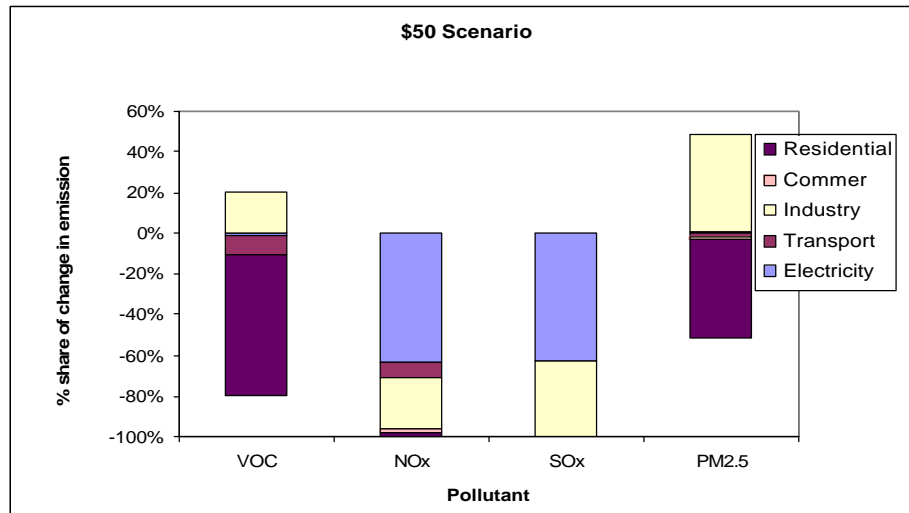
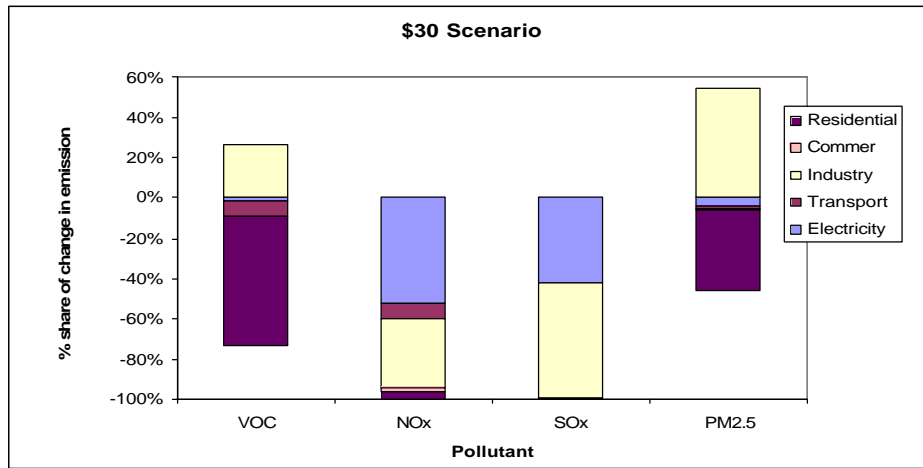
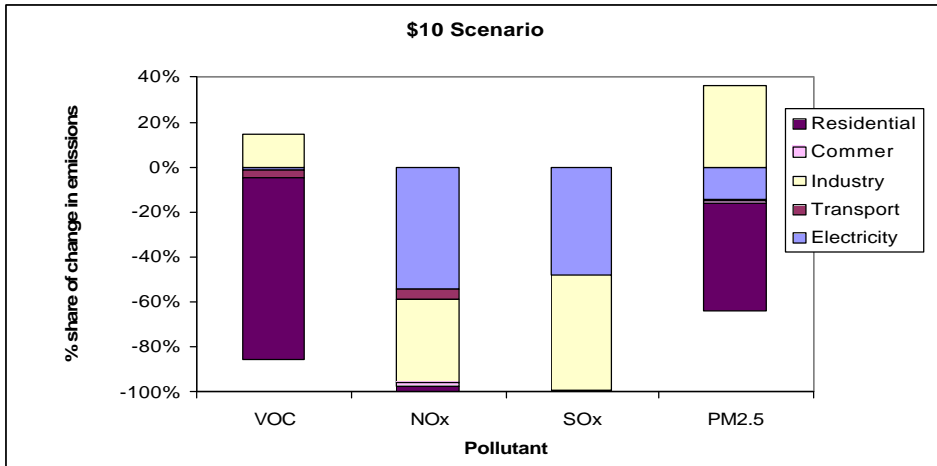
| Shadow Price                   | Ontario   |          |                   |                      |                   |                      |                   |                        |                   |
|--------------------------------|---|----------|-------------------|----------------------|-------------------|----------------------|-------------------|------------------------|-------------------|
|                                | Emissions Reduced in 2010 (kilotonnes)<br>(positive values = reduction in emissions from the BAU, negative values = increase) |          |                   |                      |                   |                      |                   |                        |                   |
| (\$ / tonne CO <sub>2</sub> e) | GHGs <sup>a</sup> (Mt)  | VOC (kt) | % change from BAU | NO <sub>x</sub> (kt) | % change from BAU | SO <sub>x</sub> (kt) | % change from BAU | PM <sub>2.5</sub> (kt) | % change from BAU |
| 10                             | 17.3  | 10.0     | 2.8%              | 25.1                 | 4.5%              | 33.0                 | 4.1%              | 1.2                    | 0.0%              |
| 30                             | 21.0  | 7.4      | 2.1%              | 29.0                 | 5.3%              | 58.9                 | 7.4%              | (0.4)                  | 0.0%              |
| 50                             | 29.0  | 11.2     | 3.2%              | 44.1                 | 8.1%              | 113.3                | 14.2%             | 0.1                    | 0.0%              |
| BAU                            | --  | 351      | --                | 546                  | --                | 798                  | --                | 83                     | --                |

<sup>a</sup> includes indirect and direct GHG emission reductions, where direct emission reductions are caused directly by an action in a sector and indirect refers to reductions associated with a reduced demand for electricity.

For example, greater VOC emission reductions are associated with the \$10 rather than the \$30 scenario. This is because, as described in section 3.1, the GHG shadow price stimulates a mix of actions that have synergistic and antagonistic effects on CAC emissions and the sum of synergistic reductions for VOCs are slightly greater at the \$10 shadow price.

In the three shadow price scenarios, the biggest changes in GHG emissions are seen in the transportation (32%), electricity (32%) and industrial (11%) sectors. In comparison, the greatest changes in CAC emissions occur in the industrial, electricity generation and residential sectors for each shadow price (see figure 7).

Figure 7. Sector share of total change in CAC emissions relative to the BAU case for the \$10, \$30 and \$50 scenarios.



Note that for most sectors and pollutants, a synergistic response in CAC emissions dominates as illustrated by the number of cases where the policy scenario indicates net reductions (net reductions in a sector are indicated by the shaded area falling below the 0% line on the y-axis, and vice versa for net pollutant increases from a sector). The exception is industry, which registers an increase in PM<sub>2.5</sub> and VOCs in each policy scenario. In this case the magnitude of increase in the pollutants has overshadowed any synergistic actions, resulting in an overall increase in emissions. By taking a closer look at what happens in specific sectors a better understanding of the nature and magnitude of CAC synergies and antagonisms can be gained.

### *Electricity*

The response to GHG shadow prices in the Ontario electricity generation sector is considerable and results in both GHG reductions and changes in CAC emissions. Because there is a significant amount of thermally generated power in this region (that is predicted to increase over time in the BAU scenario), demand reductions, fuel switching and efficiency improvements stimulated by the shadow prices lead to NO<sub>x</sub>, SO<sub>x</sub>, and VOC emission reductions with a small increase in PM<sub>2.5</sub> in the \$50 policy scenario (Table 4). The largest synergy exists for NO<sub>x</sub> and SO<sub>x</sub> emissions which are reduced by 28kt (34%) and 71.8kt (82%) respectively by 2010, in the \$50 scenario.

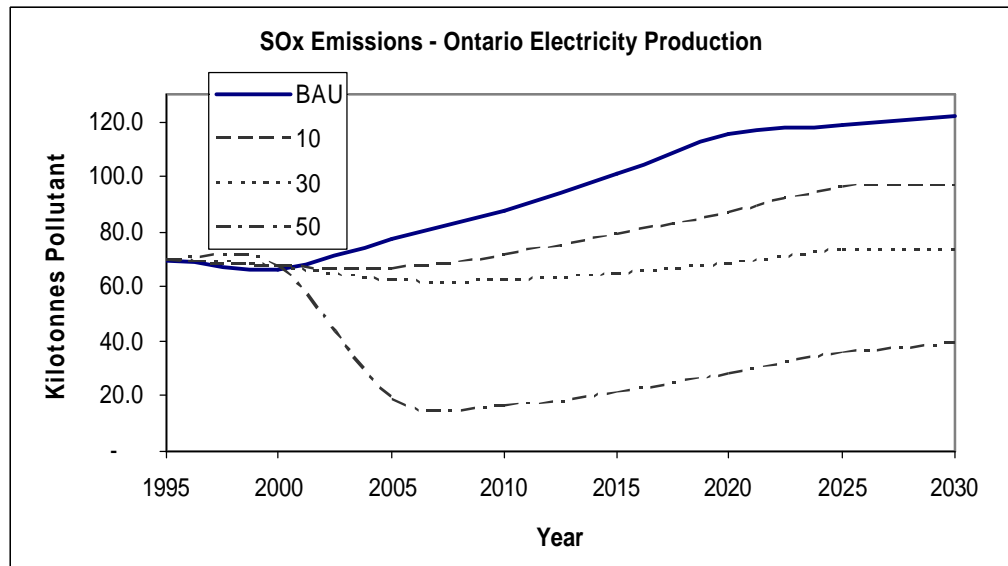
**Table 4. Emission changes in Ontario electricity generation, 2010.**

| Shadow Price                   | Emissions Reduced in 2010 (kilotonnes)  |     |                   |                 |                   |                 |                   |                   |                   |
|--------------------------------|---|-----|-------------------|-----------------|-------------------|-----------------|-------------------|-------------------|-------------------|
|                                | (positive values = reduction in emissions from the BAU, negative values = increase) |     |                   |                 |                   |                 |                   |                   |                   |
| (\$ / tonne CO <sub>2e</sub> ) | GHGs  | VOC | % change from BAU | NO <sub>x</sub> | % change from BAU | SO <sub>x</sub> | % change from BAU | PM <sub>2.5</sub> | % change from BAU |
| <b>10</b>                      | 5,968.7   | 0.2 | 24%               | 13.8            | 17%               | 15.9            | 18%               | 0.9               | 22%               |
| <b>30</b>                      | 6,832.3   | 0.2 | 20%               | 15.1            | 18%               | 25.2            | 29%               | 0.3               | 6%                |
| <b>50</b>                      | 13,122.3  | 0.1 | 16%               | 28.0            | 34%               | 71.2            | 81%               | (0.3)             | 7%                |
| <b>BAU</b>                     | --  | 0.8 | --                | 83.4            | --                | 87.6            | --                | 4.0               | --                |

Overall demand for electricity falls at higher shadow prices, with the remaining demand filled by more efficient, less CAC-intensive technologies. At higher shadow prices there is less use of single cycle oil-burning technologies and conventional coal technologies, and more natural gas. In particular, fuel-efficient combined cycle natural gas technologies gain more market share at higher shadow prices. The small increase in PM<sub>2.5</sub> (and the trend to increased PM<sub>2.5</sub> emissions at higher shadow prices) is due to an increasing use of small biomass to meet base demand for electricity.

The nature of SO<sub>x</sub> reductions over time in each of the scenarios is further illustrated in figure 8. Note that SO<sub>x</sub> emission reductions estimated with the \$50 shadow price are much greater than those under \$10 and \$30, plus large reductions are achieved earlier on (with approximately 59 kilotonnes of SO<sub>x</sub> reduced by 2005 in the policy versus the BAU scenario).

**Figure 8. SO<sub>x</sub> emissions in Ontario's electricity production sector over time**



The reduced demand for electricity, increased use of renewable energy sources, and efficiency improvements in thermally generated electricity are all GHG-reducing



actions that contribute to the decrease in SO<sub>x</sub> emissions. However, the large, early drop in SO<sub>x</sub> emissions associated with the \$50 shadow price indicates that a particularly synergistic action is penetrating more strongly in this scenario. In the \$50 scenario, extensive retro-fitting of single-cycle coal fired technologies to combined cycle natural gas occurs. More specifically, 83% of base, 73% of shoulder and 69% of peak load single-cycle coal technologies are retrofitted to combined cycle natural gas. Natural gas combustion produces far less SO<sub>x</sub> emissions than coal combustion, and switching these technologies to natural gas becomes an economical choice because the marginal cost of continuing to use coal exceeds the cost of switching to natural gas. In comparison, at the \$30 shadow price considerably less retro-fitting occurs (5% base load, 5% peak, 14% shoulder) and no retro-fitting occurs in the \$10 scenario.

There are a number of factors that together contribute to the large degree of retrofitting seen in the results for this sector, including: an element in the retrofit algorithm used in the model, uncertainty in coal and natural gas prices, the role of trade in electricity, and the ability of firms to access sufficient capital. The effect of these factors arises because the model, as any model, is a simplification of the energy-economy system. Therefore, results must be interpreted with the potential effect of these and other related factors in mind.

As indicated above, a very large amount of retrofitting (up to 83%) is seen in the \$50 scenario. This amount is larger than would be expected in CIMS given that it uses a probabilistic distribution to ensure that wholesale switching to cheaper technology options does not occur when the life-cycle cost becomes cheaper<sup>9</sup>. A contributing factor to the large scale retrofit stems from the algorithm that describes the retrofitting competition in CIMS. In order to represent that retrofit decisions may be made in each year of a simulation, rather than only once at the end of a five year period, the retrofit estimates produced at the end of each 5-year iteration are in essence multiplied by 5<sup>10</sup>.

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<sup>9</sup> This phenomenon is referred to as “penny-switching” and is often seen in linear programming models.

<sup>10</sup> Contact the author for further details describing the retrofit algorithm (mtisdale@sfu.ca).

This factor helps produce realistic estimates of retrofitting when the life-cycle costs of the technology options being compared are significantly different. However, when the life-cycle costs of the parent and retrofit options are very close (as is the case in the \$50 scenario) the factor of five amplifies the degree of retrofit beyond what would be expected. For the Ontario electricity sector in the \$50 scenario, when the factor of 5 is removed, the estimated degree of retrofitting from single cycle coal to combined cycle natural gas drops from 83% to 17% for base technologies. Accordingly, the retrofitting algorithm is currently being reviewed and updated to correct for the extreme response seen in cases where the life-cycle costs of the parent and retrofit technology are similar.

The estimated degree of retrofitting may also be amplified by the forecasted relative prices of coal and natural gas that are included in the model<sup>11</sup>. It is now believed that the forecasted natural gas and coal prices were too low and too high respectively for the Ontario electricity sector model, leading to a somewhat overstated potential for retrofitting in this sector. The details regarding the uncertainty in fuel prices are discussed further in section 3.4.3.

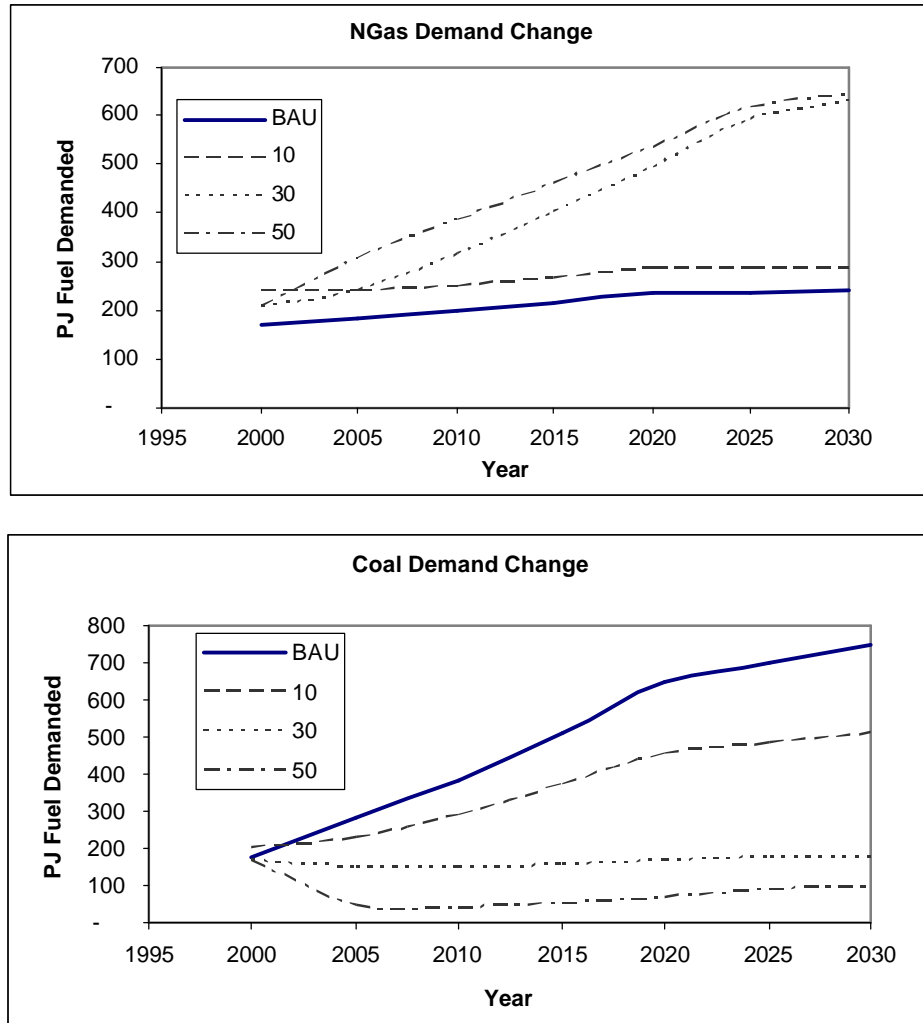
Two other considerations that would affect the degree and speed of retrofitting that were not reflected in the analysis are the role of trade in electricity, and access to financing. In response to the shadow price, Ontario could purchase electricity from Quebec or the United States, and would likely pursue this option if it were cheaper than retrofitting existing coal plants to combined cycle natural gas. This would shift at least some of the related emissions out of Ontario either into hydro-dominated Quebec (very low emissions associated with electricity production) or to the US. Also, whether or not electricity generators could access the capital required to finance the retro-fitting of their plants in such a short time period is not reflected in the model, therefore the speed and degree of retrofitting estimated is likely overestimated.

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<sup>11</sup> The forecasted prices of natural gas and coal were taken from Canada's Emissions Outlook: An Update

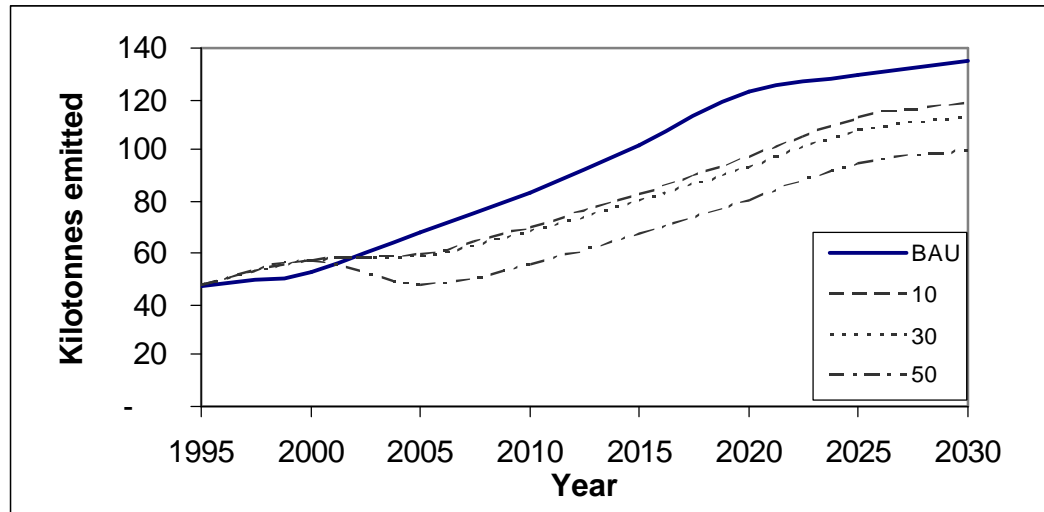
Not surprisingly, the demand for coal decreases in the policy scenarios with the far greater decrease in the \$30 and \$50 case commensurate with the degree of retrofitting to combined cycle natural gas seen in these scenarios. This is mirrored by a greater increase in natural gas demand for the \$30 and \$50 scenario (see figure 9), and a less pronounced increase from the BAU for the \$10 scenario.

**Figure 9. Change in the demand for coal and natural gas in the Ontario electricity generation sector over time**



NO<sub>x</sub> emission reductions show a similar trend (figure 10), although the difference between the reductions in the \$50 and the other shadow price scenarios is less pronounced. This is because the difference in NO<sub>x</sub> emissions between coal and natural gas is smaller than for SO<sub>x</sub>.

Figure 10. Change in NO<sub>x</sub> emissions over time in Ontario electricity generation.



### Industry

As indicated earlier, the industrial sector is responsible for a great deal of the change seen in CAC emissions in the policy scenarios (up to 40% as illustrated in figure 7). However, because this sector is comprised of various different industries each with different technology stocks, the responses to the GHG shadow prices are varied in magnitude and direction. As indicated in table 5, most CACs are reduced in the policy scenarios, with the exception of PM<sub>2.5</sub> and VOCs which increase.

Table 5. Emission changes in Ontario industrial sector, 2010

| Shadow Price<br>(\$ / tonne CO <sub>2</sub> e) | Emissions Reduced in 2010 (kilotonnes)  |                            |       |                 |                 |                   |
|--|---|----------------------------|-------|-----------------|-----------------|-------------------|
|  | (positive values = reduction in emissions from the BAU, negative values = increase) |                            |       |                 |                 |                   |
|  | Direct <sup>a</sup> GHGs  | Indirect <sup>b</sup> GHGs | VOC   | NO <sub>x</sub> | SO <sub>x</sub> | PM <sub>2.5</sub> |
| 10   | 3,017   | 290                        | (2.0) | 9.3             | 17.0            | (1.6)             |
| 30   | 3,758   | 255                        | (4.1) | 10.1            | 33.6            | (2.7)             |
| 50   | 4,196   | 197                        | (3.9) | 11.1            | 41.7            | (2.5)             |

<sup>a</sup> direct GHGs refer to reductions that are occur in this sector as result of an action

<sup>a</sup> indirect GHGs refer to reductions that are due to a decrease in demand for electricity in this sector

(which translates into emission reductions in the electricity sector)

A closer look at the different industrial sub-sectors shows that the response to GHG shadow prices is varied. For example, SO<sub>x</sub> emission reductions are seen in the metal smelting, mining, and chemicals manufacturing industries, while SO<sub>x</sub> emissions increase in petroleum refining, and “other manufacturing”. Therefore, the analysis of this sector will focus more on the specific industries where key synergistic and antagonistic actions were noted, namely metals smelting and refining, mining, natural gas transmission, and “other manufacturing”. Other manufacturing includes smaller industries that do not consume enough energy to fit into their own sub-sector classification in the model. The industries that make up the “other manufacturing” sub-sector vary by region.

### *Metal Smelting and Refining*

The main CAC produced in the metals industry is SO<sub>x</sub>. Metal smelting and refining is the largest industrial source of SO<sub>x</sub> in Ontario, contributing 463kt of a total of 798kt in the business-as-usual scenario (69%). However, as show in table 6, the policies tested induce little change in SO<sub>x</sub> emissions, causing reductions between 0.5% and 1.7%. Although these reductions are such a small change from the BAU, because the metals industry is a large producer of SO<sub>x</sub> to begin with, the effect of these reductions on SO<sub>x</sub> emissions in Ontario is considerable (7% to 10% of the estimated net reduction in SO<sub>x</sub> emissions in Ontario).

**Table 6. Emission changes in the Ontario metal smelting and refining industry.**

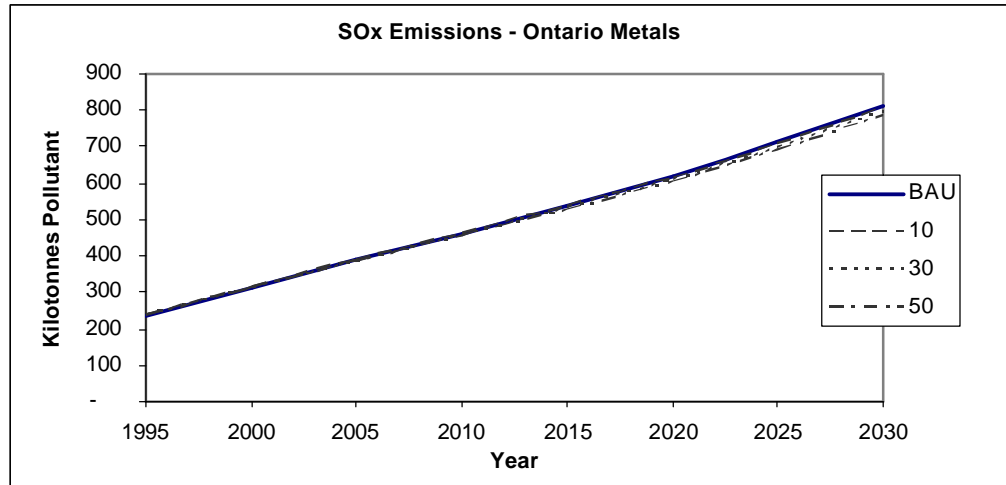
| <b>Shadow Price</b>                 | <b>Emissions Reduced in 2010 (kilotonnes)</b>                                       |                       |                          |                                     |
|-------------------------------------|---|-----------------------|--------------------------|-------------------------------------|
|                                     | (positive values = reduction in emissions from the BAU, negative values = increase) |                       |                          |                                     |
| <b>(\$ / tonne CO<sub>2</sub>e)</b> | <b>GHGs<sup>a</sup></b>   | <b>SO<sub>x</sub></b> | <b>% change from BAU</b> | <b>% of net regional reductions</b> |
| <b>10</b>                           | 43  | 2.3                   | 0.5%                     | 7%                                  |
| <b>30</b>                           | 69  | 5.8                   | 1.2%                     | 10%                                 |
| <b>50</b>                           | 79  | 8.0                   | 1.7%                     | 7%                                  |
| <b>BAU</b>                          | --  | 463.2                 | --                       | --                                  |

<sup>a</sup> includes indirect and direct GHG emission reductions, where direct emission reductions are caused directly by an action in a sector and indirect refers to reductions associated with a reduced demand for electricity.

To understand why such small reductions are seen in such a large SO<sub>x</sub>-producing industry, the key sources of SO<sub>x</sub> emissions must be understood along with the actions that occur in the policy scenarios. The actions that cause the small change in SO<sub>x</sub> emissions in the policy scenarios are fuel-switching out of coal and oil and into electricity, which is CAC-free in its end-use. For example, one such action is a switch into electric arc furnaces for copper smelting from hearth roasters and fluidized bed technologies which rely more on fossil fuels.

However, because the majority of SO<sub>x</sub> emissions from metal smelting and refining result from process sources, fuel-switching actions have little effect on total SO<sub>x</sub> emissions. (Figure 11 illustrates just how small the changes in SO<sub>x</sub> emissions over time are in the policy scenarios). For example, there are two processes that can be used in metal smelting to separate metal concentrates from sulphur and oxygen compounds in the ore and remove impurities: pyro- or hydrometallurgy. As the names suggest, pyrometallurgy involves the use of heat, while hydrometallurgy uses a chemical leaching process. In hydrometallurgy, sulphur is reduced to its pure elemental form (solid state) and therefore SO<sub>x</sub> emissions are negligible when compared to the pyrometallurgical process that uses high temperature reactions with air to concentrate the metal (Nyboer 1997), releasing SO<sub>x</sub> in the off-gas.

Figure 11. Change in SO<sub>x</sub> emission over time, Ontario metal smelting and refining.



Two actions that could stimulate a greater reduction in SO<sub>x</sub> emissions are an increased penetration of hydrometallurgy, or increased sulphur recovery. The most common end-of-pipe SO<sub>x</sub> abatement technique is to vent gases to a sulphuric acid plant, or a sulphur recovery plant (U.S. EPA, 2000). However, the factors that determine whether sulphur recovery is feasible are dictated by the market (price) for sulphur or sulphuric acid as well as specific regulations limiting SO<sub>x</sub> emissions, not whether or not GHG emissions prices are changing. Alternatively, if the shadow prices stimulated an increased penetration of hydrometallurgical process technologies, SO<sub>x</sub> emissions would decrease more dramatically. However, because there is little difference in the GHG emissions produced by these processes, a change in process technologies did not occur in the model. Thus, SO<sub>x</sub> emissions in metal smelting and refining showed very little change as they remain dominated by process sources.

### *Mining*

The policy simulation results in the mining industry provide an interesting contrast to those seen in metal smelting and refining. In contrast to the metals industry, mining contributes a very small proportion of total industrial SO<sub>x</sub> emissions in Ontario (8%, or 52.2 kt in 2010), yet contributes relatively large SO<sub>x</sub> emission reductions in the policy



scenarios (illustrated in table 7).

**Table 7. Emission changes in the Ontario mining industry**

| <b>Shadow Price</b>                 | <b>Emissions Reduced in 2010 (kilotonnes)</b>                       |                       |                          |                                     |
|-------------------------------------|---|-----------------------|--------------------------|-------------------------------------|
|                                     | (positive values = emissions reduction, negative values = increase) |                       |                          |                                     |
| <b>(\$ / tonne CO<sub>2</sub>e)</b> | <b>GHGs<sup>a</sup></b>   | <b>SO<sub>x</sub></b> | <b>% change from BAU</b> | <b>% of net regional reductions</b> |
| <b>10</b>                           | 170.8   | 27.7                  | 53%                      | 84%                                 |
| <b>30</b>                           | 182.1   | 28.4                  | 54%                      | 48%                                 |
| <b>50</b>                           | 189.0   | 29.0                  | 56%                      | 26%                                 |
| <b>BAU</b>                          | --  | 52.2                  |                          |                                     |

<sup>a</sup> includes indirect and direct GHG emission reductions, where direct emission reductions are caused directly by an action in a sector and indirect refers to reductions associated with a reduced demand for electricity.

The key GHG-reducing action that causes this drop in SO<sub>x</sub> emissions (reduced by up to 56% from the BAU in the \$50 scenario) is a change in iron agglomeration technology. Specifically, the shadow prices induce a shift out of sintering and oil-fired pelletization technologies into gas-fired pelletization. Sintering and pelletization are methods of agglomeration used to remove unwanted compounds (such as sulphur) from the ore and form it into larger, cohesive units (Nyboer, 1997). Sintering requires the use of coal and the associated SO<sub>x</sub> emissions are much higher, than from natural gas-fired agglomeration. Because the GHG emissions from sintering are higher than those from the natural gas-fired pelletization process, the GHG shadow prices favour the use of the less CAC-intensive pelletization technology. This synergy in process-based CAC emission reductions is in contrast to the metals industry where no change in process technologies occurred because there was little difference in the GHG emissions associated with them.

### *Natural Gas Transmission*

A final important synergy between GHG and CAC emission reduction is seen in the natural gas transmission sector. Only transmission of natural gas to and from other

regions occurs in Ontario; therefore, the main emissions in this sector are VOCs and NO<sub>x</sub> which are produced when natural gas is combusted to drive the compressors and pumps that in turn move the natural gas along the pipeline. Table 8 presents the changes in VOCs and NO<sub>x</sub> emissions in response to the shadow prices.

**Table 8. Emission changes in Ontario's natural gas transmission industry**

| Shadow Price<br>(\$ / tonne CO <sub>2</sub> e) | Emissions Reduced in 2010 (kilotonnes)<br>(positive values = emissions reduced, negative values = increase) |      |                   |                          |                 |                   |                          |
|--|---|------|-------------------|--------------------------|-----------------|-------------------|--------------------------|
|  | GHGs  | VOCs | % change from BAU | % of net regional change | NO <sub>x</sub> | % change from BAU | % of net regional change |
| <b>10</b>                                      | 2495.1  | 2.4  | 53%               | 24%                      | 9.8             | 53%               | 39%                      |
| <b>30</b>                                      | 2685.3  | 2.6  | 58%               | 35%                      | 10.7            | 59%               | 37%                      |
| <b>50</b>                                      | 2835.2  | 2.8  | 62%               | 25%                      | 11.4            | 63%               | 26%                      |
| <b>BAU</b>                                     |   | 4.5  | -                 |                          | 18.1            | -                 |                          |

Reductions in VOCs and NO<sub>x</sub> emissions are achieved (up to 62% and 63% in the \$50 scenario) as a result of GHG-reducing actions in this sector. For example, one key action in this industry is to replace natural gas fired turbines, used to help ‘propel’ the natural gas, with electrically driven alternatives. Other actions include replacing older compressors with newer more efficient alternatives, or improving the flow efficiency of the pipeline.

### *Other Manufacturing*

In contrast to the synergies discussed above, there are significant GHG-reducing actions that have an antagonistic effect on CAC emissions. For example, in the “other manufacturing” sub-sector, GHG-reducing actions cause a net increase in most CACs with the exception of SO<sub>x</sub> emission reductions in the \$30 and \$50 scenarios (table 9). By far the greatest contributors to the increase in CACs are changes in the ‘other

manufacturing' sub-sector, and in particular the wood products industry<sup>12</sup>.

**Table 9. Emission changes in Ontario other manufacturing, 2010**

| Shadow Price                   | Emissions Reduced in 2010 (kilotonnes)                  |       |                   |                 |                   |                 |                   |                   |                   |
|--------------------------------|---|-------|-------------------|-----------------|-------------------|-----------------|-------------------|-------------------|-------------------|
|                                | Positive values = reduction, Negative values = increase |       |                   |                 |                   |                 |                   |                   |                   |
| (\$ / tonne CO <sub>2</sub> e) | GHGs <sup>a</sup>                                       | VOCs  | % change from BAU | NO <sub>x</sub> | % change from BAU | SO <sub>x</sub> | % change from BAU | PM <sub>2.5</sub> | % change from BAU |
| <b>10</b>                      | 75.0  | (4.0) | 12.0%             | (0.6)           | 2.7%              | (0.3)           | 1.4%              | (2.6)             | 29.2%             |
| <b>30</b>                      | 150.8   | (6.4) | 19.8%             | (0.9)           | 4.1%              | 1.6             | 7.3%              | (4.0)             | 44.9%             |
| <b>50</b>                      | 191   | (6.4) | 19.8%             | (0.7)           | 3.1%              | 3.0             | 13.8%             | (4.0)             | 44.9%             |
| <b>BAU</b>                     | --  | 32.3  | --                | 22.0            | --                | 21.8            | --                | 8.9               | --                |

<sup>a</sup> includes indirect and direct GHG emission reductions, where direct emission reductions are caused directly by an action in a sector and indirect refers to reductions associated with a reduced demand for electricity.

Driving the antagonism in CAC emissions from other manufacturing are GHG-reducing, fuel switching actions. In the wood products industry, wood waste is a readily available fuel that becomes more attractive as a source of direct heat in the shadow price scenarios. Because biomass is represented as GHG-neutral in the model (the net GHG emissions from this fuel are zero as GHGs are assumed to be taken up by growing forests and other biomass as part of the natural carbon cycle, subsequent to combustion) the shadow price makes all other GHG-producing fuels, including natural gas, comparatively less attractive. However, the CAC emissions associated with wood waste (and biomass in general) are high compared to natural gas. The resulting increase in PM<sub>2.5</sub> emissions, in particular, is so large (29.2 – 44.9% increase over BAU levels) that it contributes to an overall increase in industrial PM<sub>2.5</sub> emissions in Ontario.

The increased use of biomass fuel and the resulting antagonism for CAC emissions is even more strongly observed in the “other manufacturing” sector of B.C., and plays an important role in determining PM<sub>2.5</sub> emissions from the residential sectors in

<sup>12</sup> The wood products industry includes saw mills, lumber, veneer and wood panel manufacturing.

B.C. and Ontario. In B.C. “other manufacturing”, the increase in biomass fuels accounts for most of a 21 kilotonne increase in PM<sub>2.5</sub> emissions by 2010 in the \$50 scenario. Consequently, the magnitude of this antagonism is sufficient to result in an overall increase in PM<sub>2.5</sub> emissions in B.C. of 16 kilotonnes (2010).

It is important to note that the actual trend in PM<sub>2.5</sub> emissions in B.C. or Ontario may change when emissions that are not related to energy are considered. For example, in B.C. beehive burners are used to dispose of wood waste and produce large amounts of PM<sub>2.5</sub> (and other CACs) but are not included in the CIMS model because they do not demand or produce energy. The increased use of biomass as an energy source in “other manufacturing” means less wood waste is disposed of in bee-hive burners, offsetting the PM<sub>2.5</sub> emissions from these technologies – which should result in a net decrease in PM<sub>2.5</sub> emissions in B.C. (or other regions). In this case, these results are partial<sup>13</sup> because they only estimate CAC emissions related to energy and do not consider the non-energy related emissions that may be offset by GHG-reducing actions.

In the residential sectors of B.C. and Ontario wood-burning in stoves and fireplaces as a supplement to electric baseboard home heating increases in the scenarios causing a decrease in GHGs and an increase in PM<sub>2.5</sub>. Although the magnitude of this change is not large enough to cause an overall increase in PM<sub>2.5</sub> in the residential sector, the fact that a PM<sub>2.5</sub>-increasing action occurs in a residential area is cause for concern because the emissions occur in populated areas, increasing the potential that they will affect human health. It should be noted that in B.C. there is a provincial regulation that limits the sale of wood-burning stoves to those that are certified by the Canadian Standards Association to a low level of emissions, including particulates (Waste Management Act, 1994). The effect of this regulation is not currently included in the model; therefore, the estimated change in particulate emissions is likely overstated in B.C.. Although no other provinces have a residential wood-stove regulation, many have

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<sup>13</sup> While it is was not done for this study, CIMS could estimate the change in PM in the “other manufacturing” sector more completely by incorporating bee-hive burners into this sector of the model.

sponsored ‘change-out’ programs and a national regulation is being developed by the Canadian Council of Ministers of the Environment.

### *Transportation*

In contrast to the synergies and antagonisms described above, CAC emissions in the transportation sector show very little response to the GHG shadow prices. Transportation is the second largest source of GHGs in Ontario, and contributes the most GHG reductions in response to the shadow prices (32% of total GHG reductions in 2010). Interestingly, transportation produces significant amounts of VOCs and NO<sub>x</sub> emissions as well, yet very small changes in CAC emissions are seen in the policy scenarios. As indicated in table 10, the shadow prices induce large GHG reductions that increase with increasing shadow prices. VOCs and NO<sub>x</sub> emissions follow this trend; however, less than 3.3 kilotonnes (1.1% from BAU) of reductions are achieved for NO<sub>x</sub> and less than 2 kilotonnes (1.5% from BAU) for VOCs. Interestingly, the very small change in CAC emissions from Ontario transportation is mirrored in the transportation sectors of all regions.

**Table 10. Emission changes in Ontario transportation, 2010**

| Shadow Price                   | Emissions Reduced in 2010 (kilotonnes)                  |       |                   |                 |                   |                 |                   |                   |                   |
|--------------------------------|---|-------|-------------------|-----------------|-------------------|-----------------|-------------------|-------------------|-------------------|
|                                | Positive values = reduction, Negative values = increase |       |                   |                 |                   |                 |                   |                   |                   |
| (\$ / tonne CO <sub>2</sub> e) | GHGs  | VOCs  | % change from BAU | NO <sub>x</sub> | % change from BAU | SO <sub>x</sub> | % change from BAU | PM <sub>2.5</sub> | % change from BAU |
| <b>10</b>                      | 2965.3  | 0.5   | 0.4%              | 1.1             | 0.4%              | 0.0             | 0.0%              | 0.0               | 0.0%              |
| <b>30</b>                      | 3792.7  | 1.2   | 0.9%              | 2.2             | 0.7%              | 0.1             | 0.3%              | 0.1               | 0.6%              |
| <b>50</b>                      | 4788.0  | 2.0   | 1.5%              | 3.3             | 1.1%              | 0.1             | 0.3%              | 0.1               | 0.6%              |
| <b>BAU</b>                     | --  | 132.8 | --                | 299.5           | --                | 36.6            | --                | 17.8              | --                |

Note in table 10 that considerable GHG emission reductions are achieved, and increase with increasing shadow prices. The shadow prices stimulate the use of more fuel

efficient personal vehicles (cars and trucks) and some high efficiency diesel vehicles, all of which produce less GHG emissions than less efficient, gasoline vehicles. Further contributing to GHG reductions is mode switching from personal vehicles to urban public transport, such as buses.

The reason that such limited CAC reductions are seen in the transportation sector relates primarily to assumptions made in the BAU scenario that dictate how CAC emissions grow in the future. As indicated in section 2.2.3, the baseline scenario for transportation includes the effects of various regulations and standards on CAC emissions in transportation over time. As an example, in accordance with the Sulphur in Fuels Regulation, the sulphur content of diesel and gasoline falls from current levels to 25 ppm by 2005. To represent this change the emission factor for all diesel and gasoline road vehicles drops over time to reflect the decreasing sulphur content of the fuel. Hence, even though the vehicle-kilometers-traveled for on-road vehicles increases steadily in the BAU scenario over the period evaluated, the increase in SO<sub>x</sub> and PM<sub>2.5</sub> is very slight. Because CAC-controlling regulations are incorporated into the BAU scenario in this sector, the additional reductions of NO<sub>x</sub>, SO<sub>x</sub>, PM<sub>2.5</sub> and VOCs that can be achieved via GHG-reducing actions are limited.

Further restricting the potential for GHG-actions to induce changes in CAC emissions from transportation is the fact that the BAU scenario includes a natural vehicle stock turnover. As old vehicles are retired, new vehicles enter the system which are less polluting both because they are at the beginning of their operating life, are well-tuned and may be more fuel efficient. Thus, the estimated reductions of all CAC emissions in the transportation sector that can be achieved from GHG targeted policies are further limited.

### *Commercial*

The commercial sector is similar to the transportation sector in that very few CAC reductions are realized in the policy scenarios (as indicated in table 11) because the few GHG-reducing actions that are stimulated in this sector cause very little change in CAC production. The most significant GHG-reducing action (i.e. the capture and combustion

of landfill gas to produce energy) was modeled exogenously. However, we can assume that landfill gas capture will offset CAC production to the extent that it offsets the demand for fossil-fuels in this sector. The demand for oil and natural gas barely change in

the policy scenarios, hence the small drop in CACs results primarily from improved insulation and some fuel switching out of oil-fired and into natural gas and electricity driven space heating technologies.

**Table 11. Emission changes in Ontario commercial sector, 2010**

| Shadow Price                   | Emissions Reduced in 2010 (kilotonnes)                  |      |                   |                 |                   |                 |                   |                   |                   |
|--------------------------------|---|------|-------------------|-----------------|-------------------|-----------------|-------------------|-------------------|-------------------|
|                                | Positive values = reduction, Negative values = increase |      |                   |                 |                   |                 |                   |                   |                   |
| (\$ / tonne CO <sub>2</sub> e) | GHGs <sup>a</sup>                                       | VOCs | % change from BAU | NO <sub>x</sub> | % change from BAU | SO <sub>x</sub> | % change from BAU | PM <sub>2.5</sub> | % change from BAU |
| <b>10</b>                      | 5,218   | 4    | 3.0%              | 415             | 2.9%              | 3               | 0.2%              | 39                | 2.9%              |
| <b>30</b>                      | 5,113   | 5    | 3.7%              | 567             | 4.0%              | 5               | 0.4%              | 54                | 4.0%              |
| <b>50</b>                      | 4,812   | 6    | 4.4%              | 600             | 4.2%              | 5               | 0.4%              | 57                | 4.2%              |
| <b>BAU</b>                     | --  | 135  | --                | 14,332          | --                | 1,258           | --                | 1,350             | --                |

<sup>a</sup> includes indirect and direct GHG emission reductions, where direct emission reductions are caused directly by an action in a sector and indirect refers to reductions associated with a reduced demand for electricity

### *Residential*

Finally, the results of the policy analysis for the residential sector are presented in table 12. Overall reductions in all CACs are seen in all of the shadow price scenarios, with the more significant changes for VOCs, PM<sub>2.5</sub>, and SO<sub>x</sub> in the \$30 and \$50 scenarios.

**Table 12. Emission changes in Ontario Residential, 2010**

| Shadow Price                   | Emissions Reduced in 2010 (kilotonnes)                  |      |                   |                 |                   |                 |                   |                   |                   |
|--------------------------------|---|------|-------------------|-----------------|-------------------|-----------------|-------------------|-------------------|-------------------|
|                                | Positive values = reduction, Negative values = increase |      |                   |                 |                   |                 |                   |                   |                   |
| (\$ / tonne CO <sub>2</sub> e) | GHGs <sup>a</sup>                                       | VOCs | % change from BAU | NO <sub>x</sub> | % change from BAU | SO <sub>x</sub> | % change from BAU | PM <sub>2.5</sub> | % change from BAU |
| <b>10</b>                      | 1915.7  | 11.3 | 13.0%             | 0.7             | 4.1%              | 0.2             | 9.1%              | 2.0               | 11.2%             |
| <b>30</b>                      | 2115.8  | 10.1 | 11.6%             | 1.0             | 5.9%              | 0.3             | 14.0%             | 1.9               | 10.6%             |
| <b>50</b>                      | 2092.5  | 13.0 | 15.0%             | 1.1             | 6.5%              | 0.3             | 14.0%             | 2.5               | 14.0%             |
| <b>BAU</b>                     | --  | 86.9 | --                | 17.0            | --                | 2.2             | --                | 17.9              | --                |

<sup>a</sup> includes indirect and direct GHG emission reductions, where direct emission reductions are caused directly by an action in a sector and indirect refers to reductions associated with a reduced demand for electricity

In the residential sector the specific actions and their effect on CACs are more difficult to separate out because individual GHG-reducing actions are more subtle in their effect on CACs. In the \$30 and \$50 scenarios, switching out of oil and natural gas and into electricity contributes to ‘direct’ CAC reductions. Improved shell efficiencies, (e.g. increased insulation), more efficient furnaces and water heaters all contribute to reduced energy demand which adds to the CAC reductions. It should be noted that indirect CAC emission changes (i.e. those associated with a change in demand for electricity) were not calculated for this project. In a province like Ontario, which relies on mainly fossil-fuel based electricity, net CAC emissions from this sector could increase when indirect emissions are considered.

### **3.2.3 Regional Summary for Ontario**

As indicated in the analysis, a number of antagonistic and synergistic responses in CAC emissions can be seen when GHG-reducing actions are stimulated by climate policy. The ultimate effect of these changes on local air quality, the environment and human health depends on where geographically the changes take place, the characteristics of the local airshed, the proximity to large urban centers, and the demographic of the population affected (Burtraw and Toman, 2001).



As indicated in section 2.1, CIMS is not a spatial model and does not produce pinpoint estimates of the geographic location of emission changes. However, the approximate location and potential impact of emission changes can be deduced by combining CIMS outputs with additional knowledge of the sector in question. The following paragraphs review the changes in CAC emissions in Ontario that were discussed above, with the goal of extracting some understanding of the location and importance of these changes on local air pollution and in particular, human health.

CIMS provides estimates of emission changes associated with GHG policies to the level of specific sectors in the different regions of Canada. While the change in CAC emissions in each of the sectors in Ontario is varied, educated assumptions can be made regarding the proximity of different sectors to urban centres, and hence the potential for emission changes to impact human health. For example, the emissions from the transportation, residential and commercial sectors are released in, or in direct proximity to, urban centres. Therefore, changes in CAC emissions from these sectors have a greater probability of affecting strained urban airsheds and larger populations. Similarly, information detailing the location of large point source emitters can be used to estimate the effect of emission changes from the associated industries. As illustrated in figure 12, the three largest, coal-fired electricity generating plants are located in the densely populated area of southwestern Ontario (Ontario Ministry of Environment, 2002).

Figure 12. Locations of coal-fired electricity generating plants in southeastern Ontario.



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Combining the information about emission reductions in the different sectors with our understanding of their locations, estimates of the likely impact on local air pollution and in particular human health can be made. As depicted in figure 7, CAC reductions occur in every sector, with the exception of increased VOC and PM<sub>2.5</sub> emissions in the industrial sector. While emission reductions in the residential, transportation, and commercial sectors are relatively small, the fact that they occur in urban areas may mean these reductions could contribute to improved local air pollution and human health.

Similarly, changes in the electricity sector cannot be ignored. Because the coal fired generating plants – which increase in efficiency and switch to natural gas under the policy scenarios (as discussed above) – are located in dense urban areas, the large reductions in SO<sub>x</sub> and NO<sub>x</sub> emissions will likely improve local ambient air quality with potentially significant improvements for human health.

In comparison, the antagonistic increase in PM<sub>2.5</sub> emissions in the wood products industry may be less important for local air pollution and human health. These operations are generally located further from urban centers and closer to pulp and paper mills in the northern and western regions of the province (Ontario Ministry of Natural Resources, 1999).

*Emission Changes in the Windsor- Quebec Corridor*

The type of sector information discussed above can also be used to estimate emission changes numerically, and for a smaller region as well. For example, the Windsor-Quebec corridor in Ontario is the most densely populated area in Canada and suffers from some of the worst local air quality in the country (figure 13).

**Figure 13. Map of the Ontario portion of the Windsor-Quebec Corridor.**



----- The dotted line represents the approximate location of the corridor region.

Following the process outlined above, knowledge about the different sectors in Ontario and the location of operations was used to estimate to what extent the estimated emission changes would impact the Ontario portion of the Windsor-Quebec corridor. The results of this estimation, which was carried out using population information (residential, commercial), vehicle-kilometer-travelled data (transportation), location and production information (industrial sub-sectors), are presented in figure 14. Note that the \$10 scenario was used for this example.

**Figure 14. Relative change in CAC emissions in the Ontario portion of the Windsor-Quebec Corridor (WQC) versus the rest of Ontario (\$10 shadow price, 2010)<sup>14</sup>**

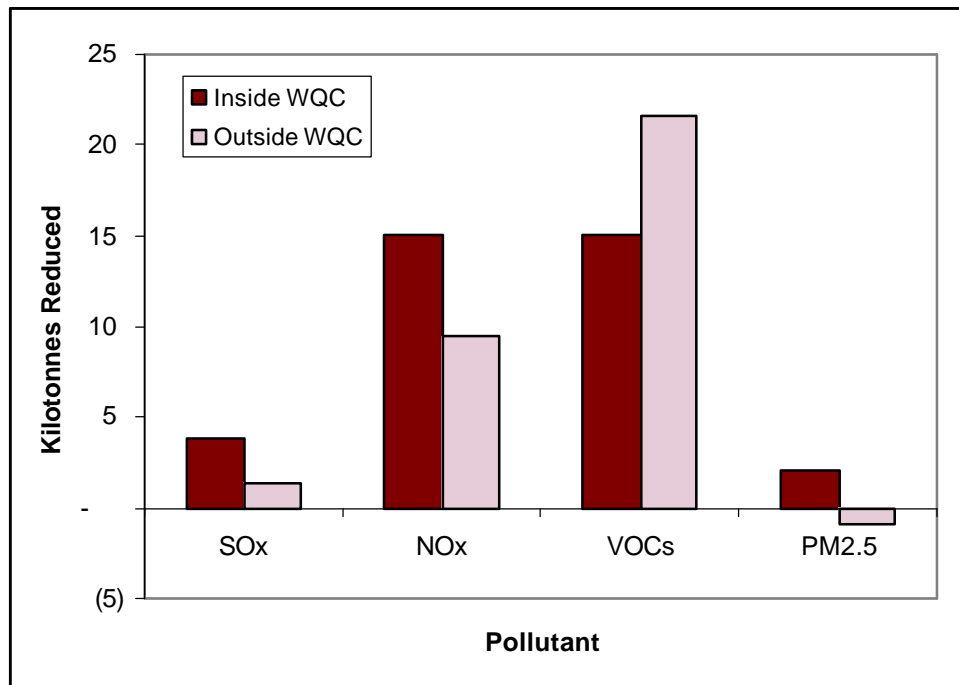


Figure 14 shows that for most pollutants the WQC benefits from a large proportion of total Ontario reductions. For example, of a total provincial reduction of approximately 25 kilotonnes of NO<sub>x</sub>, 15 kilotonnes (61%) of these reductions occur in the

<sup>14</sup> These results do not include emissions from the mining industry.

WQC. Most of the NO<sub>x</sub> reductions in the corridor are attributed to the previously discussed changes in the electricity sector. Similarly, the majority of SO<sub>x</sub> reductions occur inside the WQC (73%, or 3.9 of 5.3 total kilotonnes reduced), and can be attributed mainly to changes in the electricity sector.

Interestingly, PM<sub>2.5</sub> emissions are predicted to increase in the portion of Ontario outside of the WQC, and decrease within the WQC. The reason lies in the geographic distribution of wood product manufacturing facilities. As noted, the increased PM<sub>2.5</sub> emissions from the “other manufacturing” sector (and wood products in particular) result from increased use of biomass in response to GHG shadow prices. Because most wood product manufacturing facilities are located outside of the WQC, the PM<sub>2.5</sub> increases that occur in the shadow price scenarios do not affect the region, resulting in a net decrease of PM<sub>2.5</sub> in the WQC.

While the relative importance of emission changes in different sectors and their effect on local air pollution and human health can be deduced by broadly understanding the nature and location of sector activity, this does not replace a comprehensive understanding of the changes in ambient air quality and subsequent effect on human health and the environment. The assumptions that can be made in conjunction with the results of the CIMS analysis are useful for estimating the potential ramifications of a policy (good, bad, worse, worst) but are not a substitute for steps 4 and 5 in the analytical chain (figure 1) of ancillary effects which will more accurately determine the changes in ambient air quality and the consequences for human health and the environment.

To be most useful to decision makers, the models used to evaluate ancillary effects need to include an appropriate degree of detail, while providing information relatively quickly. Policymakers, more often than not, must make decisions in short time frames, and therefore need sufficient information to inform these decisions quickly. In some cases, for example during the early stages of GHG policy design or multiple pollutant target design, the use of a model like CIMS to estimate the direction and approximate magnitude of the ancillary effects of policies will be sufficient. Detailed and

comprehensive integrated assessment models or meteorological models can provide a more accurate, detailed understanding of the location and extent of the environmental impact of CAC emission changes but often have long computation times. Tools that strike a compromise between the quick, simple method described above and the more computationally intense integrated assessment models may be most useful because they simplify the process of estimating the ambient air quality changes and quicken the progression along the chain of analysis involved in estimating the ancillary costs and benefits of climate policy.

### **3.3 Alberta Electricity and the Role of Sequestration**

The Alberta electricity sector is an interesting case study both because it is GHG-intensive, and because it has cost-effective options to reduce these emissions. The GHG emissions are high from this sub-sector because electricity production relies on fossil fuels and heavily on coal which is abundant in the region. Furthermore, the geological characteristics of the province make deep aquifer sequestration of CO<sub>2</sub> a possibility in this region. Deep aquifer sequestration involves the capture of CO<sub>2</sub> from the flue gas of a power plant (or other emitting facility), which is transported if need be and stored in underground, geological reservoirs<sup>15</sup>. In Alberta, CO<sub>2</sub> sequestration is particularly feasible because the necessary geological reservoirs are close to thermal electricity producers (Reeve, 2000).

Table 13 presents the results of the different shadow price scenarios in terms of the GHG and CAC emission reductions from Alberta electricity. Note that large and increasing GHG emission reductions are associated with increasing shadow prices. SO<sub>x</sub>, NO<sub>x</sub>, and PM<sub>2.5</sub> emissions are reduced in the scenarios, with a slight increase in VOC emissions.

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<sup>15</sup> Appropriate storage reservoirs include depleted oil and gas reservoirs, deep and 'unmineable' coal formations, and deep saline aquifers (Reeve, 2000)

**Table 13. Emission reductions in Alberta electricity, 2010**

| Shadow Price                   | Emissions Reduced in 2010 (kilotonnes)                  |       |                   |                 |                   |                 |                   |                   |                   |
|--------------------------------|---|-------|-------------------|-----------------|-------------------|-----------------|-------------------|-------------------|-------------------|
|                                | Positive values = reduction, Negative values = increase |       |                   |                 |                   |                 |                   |                   |                   |
| (\$ / tonne CO <sub>2</sub> e) | GHGs  | VOCs  | % change from BAU | NO <sub>x</sub> | % change from BAU | SO <sub>x</sub> | % change from BAU | PM <sub>2.5</sub> | % change from BAU |
| <b>10</b>                      | 29,307.9  | (0.4) | 26.7%             | 44.4            | 40.0%             | 122.9           | 83.3%             | 5.2               | 64.2%             |
| <b>30</b>                      | 35,340.1  | (0.4) | 26.7%             | 51.2            | 46.1%             | 134.7           | 91.3%             | 5.9               | 72.8%             |
| <b>50</b>                      | 37,774.0  | (0.4) | 26.7%             | 46.0            | 41.1%             | 128.7           | 87.2%             | 5.6               | 69.1%             |
| <b>BAU</b>                     | --  | 1.5   | --                | 111.1           | --                | 147.5           | ---               | 8.1               | ---               |

The key action contributing to GHG reductions is improved efficiency in thermal-based generation of electricity. Because much of the electricity is generated through coal combustion, considerable reductions in NO<sub>x</sub>, SO<sub>x</sub>, and PM<sub>2.5</sub> can also be attributed to this action.

One might assume that, like GHGs, the CAC reductions should increase under increasing shadow prices in this sector. However, the emission reductions of NO<sub>x</sub>, SO<sub>x</sub>, and PM<sub>2.5</sub> are highest in the \$30 scenario. The reason for this counter-intuitive trend stems from the representation of carbon sequestration technologies in the model. The geology in Alberta makes deep aquifer sequestration of CO<sub>2</sub> - a process that involves stripping the carbon dioxide out of the emissions stream and burying it in a deep water aquifer - a possibility in this region (Reeve, 2000; MJKA, 2002). In the shadow price simulations, once the GHG-charge reaches \$50/tonne sequestration becomes an economically viable technology because it allows coal-based generation plants to continue operating by burying their CO<sub>2</sub> rather than further improving efficiency, fuel switching, or paying the shadow price. Hence, under the \$50 scenario CAC emissions are slightly higher because of the role that sequestration plays in freeing up fuel choices and the consequences for emission production.

The potential for decision-makers to continue to rely on ‘dirtier’ fuels, such as coal, when sequestration technologies represent a feasible option represents an important antagonism between GHG policies and CAC emissions. However, there are two important caveats to consider when interpreting the significance of this antagonism for CAC emissions and local air pollution. First, it is possible to sequester  $\text{SO}_x$  (and potentially more of the waste stream) along with the  $\text{CO}_2$ ; however, not enough is known about how this mixture of gases may react in the reservoir (Reeve, 2000). The model does not currently include this ‘enhanced’ sequestration as a technology option. Realistically, sequestering  $\text{SO}_x$  could be an important option for emitters who need to control their CAC emissions because of some other policy specifically focused on CACs. Nevertheless, the potential for, and nature of, sequestration technologies is an important consideration when evaluating the ancillary effects of climate policy alternatives.

### **3.4 Uncertainty**

Uncertainty is too often ignored in policy analysis. However, if modelling tools like CIMS are to be useful to decision makers they must provide answers to relevant policy questions, along with an understanding of the nature and effect of the assumptions that were made in reaching these conclusions. Most variables in the CIMS model have some degree of uncertainty associated with them. Therefore, it is important to understand the extent of uncertainty as well as the effect that this uncertainty has on the functioning of, and the results produced by, the model. Explicitly representing the uncertainty in model parameters more clearly illustrates that the model results are not deterministic but indicate a median point in a range of possible outcomes. Furthermore, probing the degree of uncertainty in parameters and understanding the effect of this uncertainty on the models estimates of emission changes can help to target future model development.



The sources of uncertainty that have been determined as particularly significant for results from the CIMS model include assumptions regarding (Jaccard et al., 2002):

- the baseline,
- the definitions of costs and consumer preferences,
- how consumer preferences change over time, and
- the direction and rate of technology change.

The effect of uncertainty on the estimates of GHG and CAC emission changes can be further considered in three categories: 1) model structure - variables that drive the evolution of technologies and form the simulation algorithm, 2) baseline assumptions, and 3) emission factors. The following two sections explore the uncertainty in each of these broad categories by qualitatively estimating the effect of relaxing different assumptions associated with the sources of uncertainty listed above on the CAC emission changes estimated by the model. However, because the focus of this project is on the incorporation of CAC emission estimation into the CIMS model, a more detailed discussion of uncertainty in CAC emission factors is included.

### **3.4.1 Uncertainty in variables that determine the rate of technological change**

The evolution of the technology stock over time is what drives the policy simulations and ultimately determines the mix of process characteristics and fuel demands which, in turn, dictate the resulting change in emissions. A number of variables enter into the equations that are used to determine technology stock evolution over time, including the discount rate ( $r$ ), the intangible cost factor ( $i$ ), and the variance parameter ( $v$ ). Exactly how each of these factors is included in the calculation of life-cycle costs and the technology competition scenario is described in detail in section 2.1.3.

In the development of CIMS, assumptions regarding the most appropriate value of each of  $i$ ,  $v$ , and  $r$  were made in order to best approximate the time preference of different consumers and decision makers ( $r$ ), the non-financial preferences of consumers ( $i$ ), and the relative ability of a technology to gain market share ( $v$ ). Extensive literature reviews

and market surveys were conducted to establish the value of each parameter<sup>16</sup>, and to associate different values for different sectors and technologies. Nevertheless, because consumers' preferences are heterogeneous and shift over time and with changing economic conditions, the chosen values for these are uncertain.

An extensive quantitative analysis of the uncertainty in the  $i$ ,  $v$ , and  $r$  parameters is beyond the scope of this report; however, a qualitative discussion of the effect of this uncertainty on estimated changes in CAC emissions follows and is summarized in table 14. Note that in describing the effect of differing the values for the  $i$ ,  $v$ , and  $r$  parameters in table 14 it is assumed in each case that all other model conditions and parameters remain unchanged.

**Table 14. Qualitative effect of alternative values of the parameters  $i$ ,  $v$ , and  $r$ .**

| <b>Nature of Assumption</b>  | <b>Effect on Technological Change</b>  |
|--|--|
| <b>Uncertainty in the discount rate (<math>r</math>)</b>             |  |
| Higher $r$   | Favours increased penetration of technologies with high capital cost : operating cost ratio  |
| Lower $r$  | Favours penetration of technologies with low CC:OC ratio   |
| <b>Uncertainty in the intangible cost parameter (<math>i</math>)</b> |  |
| Higher $i$   | Technology less able to serve as perfect substitute, greater inertia to penetration  |
| Lower $i$  | Technology more able to serve as substitute, less inertia to penetration   |
| <b>Uncertainty in the variance parameter (<math>v</math>)</b>        |  |
| Higher $v$   | Life-cycle cost will matter less in determining the market share of a technology. Market share will be dominated by lower cost technologies, with very few high cost technologies penetrating. |
| Lower $v$  | Life-cycle cost matters more in determining market share of technologies. More technologies with relatively high cost will capture some market share.  |

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<sup>16</sup> Nyboer (1997) and Murphy (2000) further describe how values for  $i$ ,  $v$ , and  $r$  were chosen for CIMS.

The ‘true’ value of  $r$  is something that we do not know for certain, despite extensive research to estimate the most representative value. Further complicating the choice of a value of  $r$  is the fact that discounting the future is a controversial topic. Different values of  $r$  could have a significant effect on our estimated change in CAC emissions. Recall from section 2.1.3 that the discount rate establishes the time preference associated with investments. All else remaining equal, an increase in the discount rate favours technologies with lower upfront capital costs over those with higher upfront costs and lower operating costs. For example, a more efficient boiler with high capital costs and low operating costs due to decreased energy consumption will have a harder time gaining market share if the discount rate is high. Thus a lower discount rate could result in faster, and greater decreases in CAC emissions as new, green technologies are adopted more quickly over time.

A lower value for  $i$  associated with a less energy-intensive technology, or a technology that relies on a renewable energy source, will have a similar effect on estimated changes in CAC emissions over time. If the technology has low intangible costs, (meaning that it is seen as a perfect alternative source of service in the eyes of the consumer) and comparative financial costs to other alternatives, it will more easily gain market share. If the technology has lower CAC emissions, the gain in market share will result in decreased CAC emissions as less efficient, fossil-fuel based technologies fall out of favour with consumers. In comparison, a lower variance parameter indicates that differences in life-cycle costs will bear more strongly on the ability of a technology to gain market share, creating more inertia for the penetration of high cost, potentially less polluting alternatives.

While the qualitative description of different possible values of the  $i$ ,  $v$ , and  $r$  parameters above is simple, in reality the manifestation of uncertainty and the effect on model results is more complex. Ideally a full quantitative analysis of the uncertainty in each of the parameters, and in combination (e.g. high  $r$ , low  $v$ ) should be undertaken to determine the sensitivity of the model results to changes in each parameter.

### 3.4.2 Baseline Assumptions

In this research only one baseline was tested which includes a number of assumptions regarding the growth in energy demand, GHG emissions, and CAC emissions over time. In order to test the effect of uncertainty in the baseline on the resulting estimates of emission changes, numerous model runs would be required and the time and effort to change the associated parameters would be cumbersome. Instead, the assumptions that pertain specifically to how CAC emissions are characterized in the baseline scenario and how they qualitatively affect the forecasted changes in emissions are explored below and summarized in table 15.

**Table 15. Qualitative effect of baseline uncertainty on estimated changes in CAC emissions**

| <b>Nature of Assumption</b>  | <b>Effect on BAU</b>                                     | <b>Likely effect on model outputs</b>  |
|--|--|--|
| Only calibrated to 1995 CAC emissions, not over time                                     | Nature of future CAC emissions in the BAU more uncertain | Forecasted emission changes are more uncertain farther into the future   |
| Baseline does not include changing regulations that could affect CAC emissions in future | Shift BAU-CAC emissions lower, may fall over time        | CIMS likely overestimates the emission changes over time (assuming that local air pollution will continue to be a policy priority across Canada and that new regulations will be coined) |
| Future development of abatement technologies not included                                | Shift BAU-CAC emissions lower, may fall over time        | If these technology options were included in the baseline, the related CAC emissions would either fall over time, or grow at a slower rate   |

First, the 1995 CAC emission estimates in CIMS are calibrated to the RDIS-II inventory of CAC emissions for 1995. Therefore, the CAC emissions characterized in the BAU scenario become more uncertain farther into the future because the change in these emissions over time has not been calibrated to an external, established inventory<sup>17</sup>.

Second, national or regional policies directly targeting CAC emissions may

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<sup>17</sup> While it was not available for this study, the RDIS-II forecast of CAC emissions is now established and calibration to it is an option for future model development.

develop over time. Increased future regulation of CAC emissions would mean that the BAU estimates of CACs would be lower, or may even fall over time. If we assume that future CAC policies are likely, then the CAC emission changes estimated in CIMS are likely too large.

Finally, the BAU scenario does not include the potential for the development of new, effective CAC abatement technologies over time. If these technology options were included in the baseline the related CAC emissions would either fall over time or grow at a slower rate.

### **3.4.3 Emission Factor Uncertainty**

As indicated in section 2.5, there is a great deal of uncertainty in the emission factors used to estimate CAC emission changes. Because the emission factors in this analysis represent an average relationship, the true, observed emission rates will vary with slight differences in operating conditions and other factors that are not captured in the model. This uncertainty is magnified by the fact that U.S. emission factors were used to estimate the CAC emissions from the majority of the technologies in the model, which may or not be representative of actual Canadian emissions. Furthermore, a degree of uncertainty is included in the U.S. data, and varies with the method used to develop the specific emission factor (as described in table 2, section 2.4).

The U.S. EPA qualitative rankings of emission factor uncertainty have been included in the data used in this analysis. The rankings can help inform the uncertainty analysis by indicating the relative range of possible values for the emission factor used, ranging from narrow (rankings A, B) to wide (rankings D, E) as well as the potential for the value to be biased (higher bias in D, E rankings). Factors that may cause variation in an emission factor include: the quality of the feed material or fuel, the presence of abatement technologies, the age and maintenance level of the process or combustion technology and its operating characteristics (e.g. temperature).

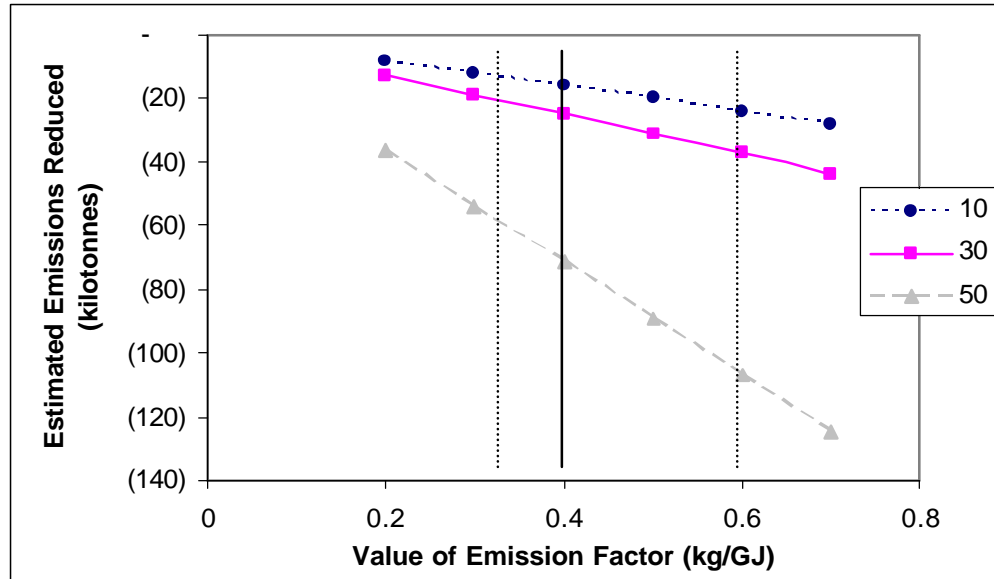
We are most interested in areas where uncertainty might greatly impact our emission predictions (change the magnitude of synergies or antagonisms), or change the relative desirability of the policy alternatives in terms of the level of CAC emission changes associated with the different shadow prices. Therefore, I have conducted sensitivity analyses on key emission factors that relate to synergistic changes in Ontario electricity SO<sub>x</sub> emissions, and the antagonism resulting from biomass use in the “other manufacturing” sector.

### *Uncertainty in Ontario Electricity SO<sub>x</sub> Emissions*

Recall from the discussion of emission reductions in the Ontario electricity sector (section 3.2.2) that GHG reducing policies produced SO<sub>x</sub> emission reductions ranging from 18 to 82% of BAU levels, and the main driver of these reductions was retrofitting existing coal technologies to combined-cycle natural gas. The magnitude of this synergy could be affected by uncertainty in the emission factor used to describe the SO<sub>x</sub> emissions from these two fuels. Emissions of SO<sub>x</sub> associated with natural gas combustion are so small that they are negligible (natural gas contains barely any sulphur), therefore the sensitivity analysis focuses on the SO<sub>x</sub> EF associated with sub-bituminous coal combustion.

To test the sensitivity of SO<sub>x</sub> emission projections to uncertainty in the coal combustion EF, the EF was varied by increments of 0.05 kg/GJ around the mean value used in the model. This variation in could illustrate the effect of higher or lower sulphur content in the coal, the presence of an abatement technology, or differences in the level of maintenance. Figure 15 presents the results of the sensitivity analysis.

**Figure 15. Sensitivity of SO<sub>x</sub> emission estimates to uncertainty in the sub-bituminous coal combustion emission factor.**



The emission factor value used in the model was 0.4 kg/GJ, and is indicated by the solid, black, vertical line in figure 15. The dashed lines in figure 15 represent the range of highest likelihood for possible values of the emission factor. The U.S. EPA rating for this EF is ‘A’, meaning that the value was determined using numerous random samples (reducing natural variability), and is relatively precise and free from bias. The quality rating indicates that the likely potential range in the emission factor should be fairly small. Furthermore, the likelihood that the emission factor would be above 0.4 kg/GJ is relatively small because the mean value already assumes a high sulphur content in the coal, and the use of abatement technologies. Furthermore, variation of the EF within the range of values indicated by the dashed vertical lines maintains calibration of SO<sub>x</sub> emissions in the Ontario electricity sector, within the specified limits.

The relationship depicted in figure 15, combined with the likely range in emission factors illustrates the effect that emission factor uncertainty can have on the magnitude of emission reductions predicted for each scenario, as well as the relative difference between the three shadow prices. Note that the emission reduction estimates for the \$10 and \$30

scenario are relatively insensitive to variation in the emission factor, while the \$50 scenario, as evidenced by the steep slope of the line, is quite sensitive. Thus, uncertainty in the SO<sub>x</sub> emission factor for sub-bituminous coal combustion has a greater effect on emission changes estimated in the \$50 scenario. The effect of emission factor uncertainty is further illustrated in table 16. A very small, 0.1 kg/GJ change in the emission factor results in a large change (~18 kilotonnes, or 0.03% change) in estimated SO<sub>x</sub> emission reductions in the \$50 scenario and a smaller change (2 and 6 kt respectively, a 0.01% change) in the \$10 and \$30 scenario.

**Table 16. Estimated emission reductions associated with different values of the SO<sub>x</sub> emission factor for sub-bituminous coal combustion in Ontario electricity generation, 2010**

| Scenario  | Emissions Reduced (kilotonnes) |                           |                        |
|-----------|--------------------------------|---------------------------|------------------------|
|           | Low EF<br>(0.3 kg/GJ)          | Average EF<br>(0.4 kg/GJ) | High EF<br>(0.5 kg/GJ) |
| <b>10</b> | 12                             | 16                        | 20                     |
| <b>30</b> | 19                             | 25                        | 31                     |
| <b>50</b> | 54                             | 71                        | 89                     |

Furthermore, note that the difference between the estimated emission reductions for the \$10 and \$30 scenarios and the \$50 scenario are higher at higher possible emission factor values. This tells us two things. First, that while the relative magnitude of reductions associated with each shadow price stays the same (i.e. least reductions associated with \$10 most with \$50) our estimate of the difference between them will be greater at higher EF values. Thus, if the EF is overestimated (i.e. the true value is less than 0.4kg/GJ), SO<sub>x</sub> emission reductions and the expected synergy between SO<sub>x</sub> and GHG reducing actions are overestimated in the analysis. Second, the difference between the reductions associated with the different shadow prices is overstated.



### *Fuel Prices*

Another key uncertainty that could affect the synergy between GHG actions and SO<sub>x</sub> reductions in the Ontario electricity generation sector is the relative prices of natural gas and coal. The price of natural gas has been highly variable in the last few years, while in comparison the price of coal has been more stable. If natural gas prices were to fluctuate beyond what is represented in the model, this could greatly impact the degree of retrofitting of single cycle coal to combined cycle natural gas. As the price of natural gas increases (all else remaining equal) the penetration of natural gas technologies and the degree of retrofitting should fall –decreasing the magnitude of SO<sub>x</sub> reductions associated with GHG-reduction policies. The effect of these fluctuating prices will indicate to decision-makers just how important fuel prices will be on the predicted co-benefits of climate policy.

Similarly, uncertainty regarding the price of coal as it pertains to electricity producers, may affect the CAC estimates in CIMS. The coal price included in CIMS in recent years was based on estimated export coal prices which are fairly high at approximately \$230 per GJ. However, many electricity producers have easy access to coal in close proximity to their operations, meaning the price of coal for these producers is actually much lower, and is closer to \$0.75 a GJ<sup>18</sup>. This is particularly true for Alberta and Saskatchewan, and less so for Ontario. Overestimating the price of coal (relative to natural gas) would have a similar effect on CAC emission estimates as described above.

### *Uncertainty in Ontario Other Manufacturing PM<sub>2.5</sub> Emission Factor*

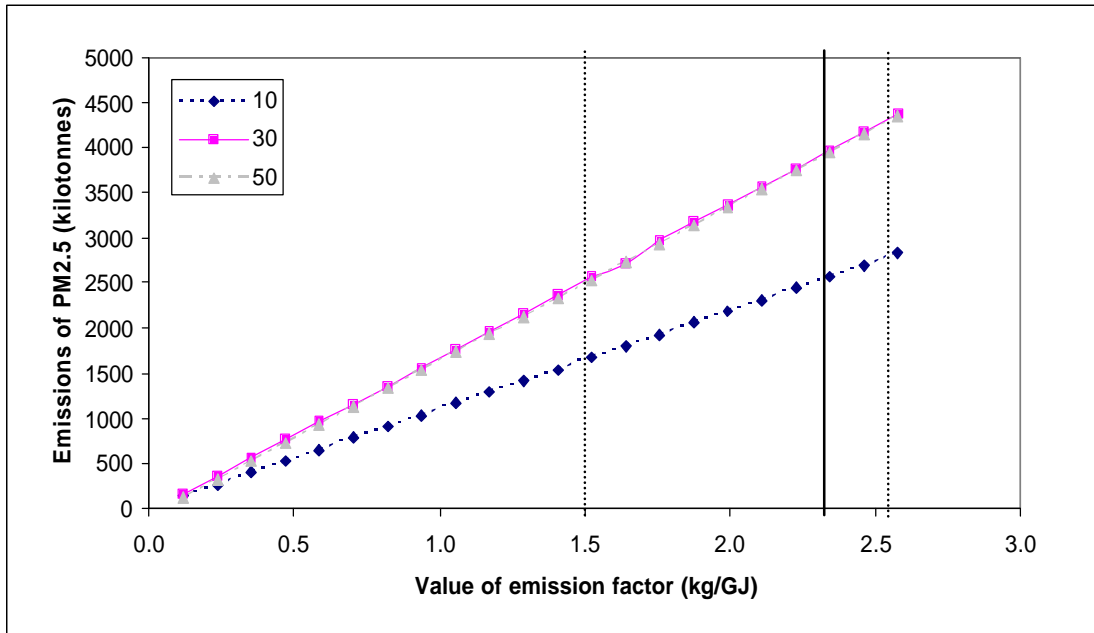
The antagonistic increase in PM<sub>2.5</sub> emissions from increased wood combustion in the “other manufacturing” sector of Ontario may also be affected by uncertainty in the related emission factor. A range of different values for the PM<sub>2.5</sub> emission factor was

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<sup>18</sup> The over estimation of coal prices in the electricity sector has been addressed and corrected in the newest version of the CIMS model; however, for this research project the higher coal prices were used.

tested for the resulting change in estimated emissions in the “other manufacturing” sector. Figure 16 and table 17 illustrate the results of the sensitivity analysis.

**Figure 16. Sensitivity of the estimated change in PM<sub>2.5</sub> emissions to uncertainty in the emission factor describing PM<sub>2.5</sub> emissions from wood combustion**



As with the sensitivity analysis for coal combustion, the likely range of potential values for the emission factor is determined by considering the data quality ranking, the model calibration, and the other assumptions that went into establishing the emission factor. The value used in the model is 2.43 kg/GJ (as indicated by the solid vertical line in figure 12), and has a data quality ranking of E, meaning that the sampling and random error are high as well as bias and imprecision. Furthermore, the calibration of PM<sub>2.5</sub> emissions in other manufacturing is maintained only for a range of values between 1.4 and 2.5 kg/GJ<sup>19</sup> (as indicated by the dotted lines in figure 16).

Within this range of ‘likely’ values for the emission factor, two trends in

<sup>19</sup> Note that the emission factors used in Ontario represent an estimated average, uncontrolled level of PM<sub>2.5</sub> emissions. Regulations that stipulate a level of particulate control for biomass plants would lower the effective emission factor and reduce uncertainty regarding its value.

sensitivity are apparent. First, the slope of all three scenario relationships are moderate, meaning that small changes in the emission factor value will translate into moderate variation in emission changes for each scenario. Second, the slopes of the \$30 and \$50 line are similar, and steeper than that of the \$10 line indicating that uncertainty in the emission factor will have a somewhat greater effect on the emissions predicted in the \$30 and \$50 scenarios than the \$10 scenario.

**Table 17. Estimated emission reductions of PM<sub>2.5</sub> associated with different values for the wood combustion emission factor in Ontario “other manufacturing”, 2010**

| Scenario | Emissions Reduced (kilotonnes)         |                      |                     |
|----------|--|----------------------|---------------------|
|          | (negative values indicate an increase) |                      |                     |
|          | Low<br>(1.4 kg/GJ)                     | Mean<br>(2.43 kg/GJ) | High<br>(2.5 kg/GJ) |
| 10       | (1.5)                                  | (2.6)                | (2.7)               |
| 30       | (2.4)                                  | (4.0)                | (4.3)               |
| 50       | (2.3)                                  | (3.9)                | (4.1)               |

As indicated in figure 16 and table 17, uncertainty has a greater effect on predicted emission reductions in the \$30 and \$50 scenarios, where a small change (+/- 0.1 kg/GJ) results in a difference of approximately 0.3 kilotonnes (or an 8% change) of estimated PM<sub>2.5</sub> emissions. Therefore, if we have underestimated the emission factor (which is less likely), the difference in emissions predicted for the different scenarios is underestimated, as are the emissions produced. More likely, we have overestimated the emission factor which means that the differences between the scenarios are overstated, and the magnitude of the antagonistic increase in PM<sub>2.5</sub> is likely smaller than we have estimated.

All of the emission factors used to estimate CACs in this research are uncertain to a degree. Therefore, further research focused on reducing the uncertainty in specific emission factors should be targeted on those that can produce the greatest improvements

to the model. Table 18 describes the relationship between the degree of uncertainty in a parameter, the significance of the uncertainty on the predicted outcome of the model, and the consequent importance of research to reduce the uncertainty. As discussed above, the emission factor for SO<sub>x</sub> production from sub-bituminous coal combustion had a small degree of uncertainty (A-rating) and a small effect on resulting estimates of SO<sub>x</sub> emissions from Ontario electricity generation. Therefore, further development of this SO<sub>x</sub> emission factor would fall in the upper left quadrant of table 18 – indicating that further development of the emission factor to decrease the uncertainty is of a low research concern. In comparison, the PM<sub>2.5</sub> EF for wood combustion in “other manufacturing” was highly uncertain (E-rating) and had a greater impact on estimated emission changes (8%). The combination of high uncertainty and higher significance to the outcome situates the PM<sub>2.5</sub> EF in the lower right quadrant of table 18, indicating a higher research concern.

**Table 18. Relationship between uncertainty in parameters, their significance to the outcome, and subsequent research concern**

|                                   | <b>Low significance to outcome</b> | <b>High significance to outcome</b> |
|-----------------------------------|------------------------------------|-------------------------------------|
| <b>Low degree of uncertainty</b>  | Low research concern               | Low research concern                |
| <b>High degree of uncertainty</b> | Lower research concern             | Highest research concern            |

(adapted from Jaccard et al. 2002, p.203)

There are hundreds of emission factors used in the CIMS model, but only limited resources available to improve their quality, or reduce their uncertainty. If the process described above to systematically target further development of emission factors is followed, these limited resources will be invested in research with the most overall value for the model.

## **Conclusion**

### **4.1 Summary**

Anthropogenic production of greenhouse gases (GHGs) and criteria air contaminants (CACs) has contributed to climate change and local air pollution - two serious threats to sustainability in Canada. The production of both GHGs and CACs is linked strongly to economic activities and in particular to fossil fuel combustion. Consequently, policies that target GHG reduction, such as those developed to pursue the targets set in the Kyoto Protocol, will necessarily affect CAC emissions. Thus, responsible decision makers must consider the ancillary effects of Canadian climate policies on criteria air contaminant (CACs) emissions before a determination of the full costs and benefits of these policies can be made.

The objective of this research was to develop a modelling tool that would simulate, through an integrated representation of the Canadian economy and energy system, the GHG-reducing actions induced by climate policy and the associated changes in CAC emissions. Criteria were established characterizing the ideal energy-economy ancillary effects estimation tool, including: technological explicitness, preference incorporation, disaggregated calculation of CAC emissions, and spatial resolution. The CIMS model served as the base modelling tool, and was enhanced with CAC emission factors which were adapted from the U.S. EPA AP-42 database and calibrated to the RDIS-II inventory of CAC emissions in Canada. The types of CAC emissions described in CIMS include fuel-based, process-based, and fugitive sources of NO<sub>x</sub>, SO<sub>x</sub>, VOCs, CO, and PM.

The resulting tool can track the synergies and antagonisms at the technology/action level and report the cumulative effect on regional emissions. Incorporating CACs into CIMS represents the first attempt at estimating CAC emission changes in Canada with a behaviourally realistic, technologically detailed model that is specific to Canada.

## 4.2 General Lessons from the Analysis

While the analysis of GHG shadow prices (\$10, \$30 and \$50 / tonne GHG) focused on the CAC changes in Ontario, the model includes all regions and sectors of the Canadian economy. The lessons learned from the analysis of Ontario can be summarized into a general understanding of the potential ramifications of climate policy on CAC emissions.

### *Synergies and Antagonisms*

The analysis showed that, contrary to a common assumption in the literature, climate policy does not always result in CAC emission reductions. Some actions induced by the GHG shadow prices, such as energy efficiency improvements and demand reductions, will cause CAC reductions. The response associated with other actions (fuel-switching, process changes) is less clear, and can be antagonistic. Table 19 summarizes the types of actions that can result in response to climate policies, and the corresponding effect on CAC emissions.

**Table 19. Summary of the effect of GHG-reducing actions on CAC emissions**

| <b>Response to Climate Policy</b>  | <b>General Effect on CAC Emissions</b>   |
|--|--|
| Improved energy efficiency   | Decrease CAC emissions   |
| Decrease output  | Decrease CAC emissions   |
| Improved maintenance<br>(e.g. to reduce fugitive emissions of from petroleum refineries) | Decrease fugitive CAC emissions (usually NO <sub>x</sub> , VOCs)   |
| Fuel switching   | CAC decrease – if switch from thermal (coal, oil, natural gas) to CAC-benign renewable like solar or hydro<br><br>CAC increase – if switch into more CAC-intensive fuel like biomass.                            |
| Change in process technologies   | CAC decrease – if switch to less CAC-intensive process<br><br>CAC increase – if switch to more CAC-intensive process<br><br>CAC neutral – if both process technologies have similar CAC emission characteristics |

Synergistic reductions of CAC emissions associated with GHG shadow prices can occur through actions such as efficiency changes, fuel-switching, improved maintenance and process changes. In sectors characterized by high fossil-fuel use, small efficiency improvements can result in large CAC reductions, as seen by the synergistic CAC reductions (SO<sub>x</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>) in the Alberta electricity sector. As illustrated by the large SO<sub>x</sub> emission reductions in the Ontario electricity sector, fuel-switching can also produce significant CAC reductions when it results in an increased prevalence of less CAC-intensive fuels.

In sectors that produce large amounts of process-based CAC emissions, the change in CACs associated with GHG-reducing actions is less clear. The switch from sintering to pelletization in the Ontario mining industry is an example where a process change resulted in GHG reductions and considerable SO<sub>x</sub> reductions as well. In contrast, if the CAC-producing process is not also associated with net GHG production, a climate policy will have little or no effect on the market share of the process technology, and will not contribute to a change in CAC emissions from the sector of focus. This phenomenon was illustrated in the Ontario metals industry. Although this sector is a big contributor to SO<sub>x</sub> emissions in Ontario, it produced relatively small, efficiency based reductions of SO<sub>x</sub> in response to the GHG shadow prices because the main source of SO<sub>x</sub> emissions was a process technology with relatively low GHG emissions. Note, however, that process-based GHG-actions can just as easily produce an increase in CAC emissions if the opposite is true, and the process(es) favoured by the GHG-policy are CAC-intensive.

Some specific antagonisms pointed out in the analysis that should be carefully considered when designing climate policy include the use of biomass fuels and the potential for deep-aquifer or underground carbon sequestration. Because biomass is often considered a 'GHG-neutral' fuel over the time scale considered, climate policies can stimulate an increase in biomass-based combustion technologies which may dramatically increase CAC emissions. The use of biomass is more likely in sectors where the fuel is readily available and the technologies are accessible – such as in the wood products industry (other manufacturing) and residential heating. The potential for increased biomass combustion for energy production to offset other, more CAC-intensive technologies (like beehive burners) must also be considered.

Sequestration technologies can produce an antagonistic increase in CAC emissions, if the technologies are characterized as only removing CO<sub>2</sub> from the exhaust gas stream, and become an economic alternative to other abatement options. The potential for sequestration to also capture and store other pollutants (such as SO<sub>x</sub>) may offset the need to be concerned with this antagonism.



Finally, some sectors showed a relatively neutral CAC response to the GHG shadow prices. This can occur when the baseline scenario incorporates actions and existing regulations that cause CAC reductions, as in the transportation sector.

Ultimately, the total change in CAC emissions in a sector or region will depend on the relative magnitude of synergistic and antagonistic responses to a climate policy. As summarized in table 20, the net result is simple despite the complex and differing effect of the actions taken to reduce GHGs.

**Table 20. Relative magnitude of synergistic and antagonistic response in CAC emissions to GHG-reducing actions and the effect on total sector or region emissions**

| <b>Relative magnitude of Synergistic/Antagonistic Actions</b> | <b>Cumulative Result on CAC Emissions</b> |
|---|---|
| S > A   | Decrease                                  |
| S = A   | Neutral                                   |
| S < A   | Increase                                  |

If the CAC reductions from the sum of all synergistic actions in the region/sector are greater than the sum of CAC increases from antagonistic actions, the net result will be a decrease in CAC emissions and an ancillary benefit associated with the climate policy option. However, it should be noted that the net result may be different for each CAC pollutant; therefore, the guidelines summarized in table 20 apply individually to each pollutant as well.

*Regional Interpretation of Results*

As discussed in section 3.2.3, the regional relevance of emissions changes can be deduced by combining an understanding of the sectors that realize CAC changes, and the proximity of the sector activity to urban centers. An increase in a CAC pollutant in a sector that is inherently urban in nature (i.e. residential, commercial, transportation) will likely impact urban air sheds more severely with greater consequences to human health.

In some cases, additional information (such as the location of coal-fired generating stations in Ontario electricity production) can be added to further understand the significance of specific actions (i.e. switch from coal to natural gas generation) and the implications for local air pollution.

CAC estimates were disaggregated to a finer geographic level by combining CIMS estimated CAC emission changes with additional information describing the population of the region, the likely geographic location of sector activities, and production levels of facilities in the Windsor-Quebec Corridor. This type of simplified approach is valuable when decision makers require a general understanding of the spatial distribution of emission changes and the potential for human and environmental impact in a timely manner. However, this approach can not replace steps 4-6 of the ancillary effects chain of evaluation (ambient air quality modelling, estimation of environmental and health effects, and valuation) when a complete and comprehensive evaluation of the full costs and benefits of a climate policy is required.

### *Uncertainty*

To more fully explore the limitations of the CAC-CIMS modelling tool, the uncertainty in the model structure and emission factor data was explored. The model parameters that drive the evolution of technologies in the model (i.e.  $i$ ,  $v$ , and  $r$ ) and the effect of uncertainty in these variables on the estimates of CAC emission changes were briefly and qualitatively discussed.

Because this research is a first attempt at developing technology-specific CAC emission factors (EFs), the uncertainty in emission factors was explored and a process for targeted improvement in the EFs presented. The qualitative rankings of CAC emissions factors, as specified by the U.S. EPA, can be used in conjunction with sensitivity analyses to determine which EFs are most ‘uncertain’ and also have a relatively large impact on the model’s estimate of CAC emission changes. The EFs that meet these two criteria are good candidates for further research to reduce uncertainty regarding their value, because they will contribute the most to improving the overall ‘accuracy’ of the representation of

CAC emission changes in CIMS. Ultimately, considering the uncertainty in the model structure and emission factors and systematically reducing the uncertainty in key parameters will refine the model and make it a more useful tool for policy design and evaluation.

### **4.3 Recommendations for Future Research**

As mentioned, this project represents the first time that CACs have been incorporated into a technology specific, behaviourally realistic, energy-economy simulation model for Canada. As such, there are a number of potential avenues for future research that would improve the quality of the analysis and expand the types of policy questions that can be addressed.

#### *Quantitative analysis of uncertainty in the algorithm parameters*

Although the results presented in this report are unique estimates, they are in fact uncertain and should be interpreted as a point in a possible range of emission reductions. A full, quantitative analysis of the magnitude of this uncertainty would be a useful extension as it would provide improved understanding of the range of the ancillary effects of the climate policies tested. In particular, further analysis of the effect of uncertainty in the algorithms that drive technology change should be pursued.

#### *Use of data specific to Canada*

The lack of sufficiently detailed Canadian data necessitated the use of U.S. EPA AP-42 EFs. However, some experts feel that for a number of sectors and processes the U.S. values do not accurately represent Canadian emissions. Where possible, and if justified by the sensitivity analysis described above, EFs based on measurements taken from Canadian technologies should be developed and incorporated into the model. The approach to identifying uncertain emission factors with a significant effect on the model's CAC estimates outlined above will help target the process, and make the best use of the resources required to develop Canadian specific EFs.

### *Better reconciling of assumptions between CIMS and RDIS-II*

As mentioned in the methodology, the underlying assumptions of the RDIS-II CAC Inventory were unavailable to compare with those included in CIMS. Consequently, the calibration of the CAC data used in the model may not be as representative or accurate as it could otherwise have been. A detailed understanding of the assumptions included in the RDIS-II database (i.e. fuel demand, sector output) could greatly refine the calibration of CIMS CAC emission estimates. Also, calibrating to the RDIS-II forecast will improve the CAC reference case over time and decrease the uncertainty in estimated emission changes over time.

### *Representation of CAC control technologies (extension)*

Abatement technologies (e.g. scrubbers, baghouses, etc.) were not included as separate technologies in the model, and as such did not factor into estimates of technology penetration, fuel demand or costs. However, if these technologies were fully represented<sup>20</sup> in CIMS (including their capital and operating costs, fuel demand, and effect on emission) they would impact the competition for market share and the resulting effects of policies. As a result, a larger array of policy questions could be addressed; including a comparison of the effectiveness of CAC-focused versus GHG-focused policies (Gielen, 2002), and the analysis of multiple emission reduction strategies (MERS). Furthermore, the potential for synergies and antagonisms between the two policy targets could be more fully explored (For example, actions to reduce CACs such as the use of a scrubber, which in turn demands energy, can result in increased GHGs if this energy is supplied by fossil fuels).

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<sup>20</sup> The range of control technologies available in the model should reflect the actual range of options available to plant operators (i.e. regulation may require the use of a specific technology, in which case there would be no competition required)

### *Develop an exogenous tool to Improve spatial resolution of estimates*

Finally, the ability of CIMS to estimate emission changes at a fine level of spatial resolution was explored. Emission changes are estimated at the level of sectors in a region, not at the level of airshed, which would be ideal for estimating changes in ambient air quality and the subsequent steps in the chain of analysis for evaluating the ancillary costs and benefits of climate policy. Changing CIMS to produce emission estimates at this level of spatial detail would add large amounts of data and detail to the model which would increase computation times and the time required to evaluate and understand the results.

A more appropriate approach to enhancing the geographic resolution of CAC estimates would be to develop a tool, exogenous to the model that could take CIMS estimates and combine these with an understanding of airshed locations, regional populations, and sector details. As indicated, the simplified approach is valuable as a time-saving option to provide a general understanding of the distribution of emission changes, but cannot replace steps 4-6 of the ancillary effects chain of evaluation (ambient air quality modelling, estimation of environmental and health effects, and valuation). An exogenous tool would provide a more detailed and accurate understanding of the spatial location of emission changes and would feed into a more complete and comprehensive evaluation of the full costs and benefits of a climate policy.

The findings summarized in this report emphasize the role that technology specific, behaviourally realistic, hybrid energy-economy modelling can play in evaluating the ancillary effects associated with GHG reduction policies. More aggregate approaches to estimating CAC changes are less likely to capture the technology specific synergies and antagonisms that drive regional and sectoral changes in emissions. Understanding the relative importance of technology-level actions provides policymakers with a deeper understanding of the effects of climate policy and will ultimately lead to better estimates of ancillary benefits, and sounder climate policy design.



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## Appendix A More about CIMS

**Table 1. Regions and sectors included in the CIMS model**

An X indicates that the sector/region is included in CIMS.

|  | British Columbia | Alberta | Saskatchewan | Manitoba | Ontario | Quebec | Atlantic |
|--|------------------|---------|--------------|----------|---------|--------|----------|
| <b><i>Energy Demand Sectors</i></b>                |                  |         |              |          |         |        |          |
| <b>Residential</b>                                 | X                | X       | X            | X        | X       | X      | X        |
| <b>Commercial</b>                                  | X                | X       | X            | X        | X       | X      | X        |
| <b>Transportation</b>                              | X                | X       | X            | X        | X       | X      | X        |
| <b>Industrial</b>                                  |                  |         |              |          |         |        |          |
| Metal Smelting and Refining                        | X                | --      | --           | X        | X       | X      | X        |
| Mining   | X                | --      | X            | X        | X       | X      | X        |
| Iron and Steel Production                          | --               | --      | --           | --       | X       | X      | --       |
| Chemical Product Manufacturing                     | X                | X       | --           | --       | X       | X      | --       |
| Pulp and Paper                                     | X                | X       | --           | --       | X       | X      | X        |
| Industrial Minerals                                | X                | X       | --           | --       | X       | X      | X        |
| Coal Mining  | X                | X       | X            | --       | --      | --     | X        |
| Other Manufacturing                                | X                | X       | X            | X        | X       | X      | X        |
| <b><i>Energy Supply and Conversion Sectors</i></b> |                  |         |              |          |         |        |          |
| Electricity  | X                | X       | X            | X        | X       | X      | X        |
| Natural Gas Extraction and Transmission            | X                | X       | X            | X        | X       | X      | X        |
| Petroleum Refining                                 | X                | X       | X            | X        | X       | X      | X        |

## Appendix B

## CAC Data Used in the Model

Table 1. Fuel Combustion CAC Emission Factors for Selected Fuels

|                     |  | Natural Gas |       |       |       |                     |  | Heavy Fuel Oil |       |       |       |
|---------------------|--|-------------|-------|-------|-------|---------------------|--|----------------|-------|-------|-------|
|                     |  | Sector      |       |       |       |                     |  | Sector         |       |       |       |
| Pollutant           |  | Elec        | Comm  | Res   | Ind   | Pollutant           |  | Elec           | Comm  | Res   | Ind   |
| CO                  |  | 0.17        | 0.04  | 0.02  | 0.04  | CO                  |  | 0.014          | 0.014 | 0.014 | 0.014 |
| VOCs                |  | 0.0009      | 0.002 | 0.002 | 0.002 | VOCs                |  | 0.036          | 0.003 | 0.003 | 0.001 |
| NO <sub>x</sub>     |  | 0.14        | 0.04  | 0.04  | 0.08  | NO <sub>x</sub>     |  | 0.13           | 0.157 | 0.157 | 0.157 |
| SO <sub>x</sub>     |  | 0.000       | 0.000 | 0.000 | 0.000 | SO <sub>x</sub>     |  | 0.8            | 0.8   | 0.8   | 0.8   |
| PM <sub>Total</sub> |  | 0.003       | 0.003 | 0.003 | 0.003 | PM <sub>Total</sub> |  | 0.93           | 0.06  | 0.06  | 0.06  |
| PM <sub>10</sub>    |  | 0.003       | 0.003 | 0.003 | 0.003 | PM <sub>10</sub>    |  | 0.66           | 0.04  | 0.04  | 0.05  |
| PM <sub>2.5</sub>   |  | 0.003       | 0.003 | 0.003 | 0.003 | PM <sub>2.5</sub>   |  | 0.48           | 0.01  | 0.01  | 0.03  |

|                     |  | Light Fuel Oil |       |       |       |                     |  | Wood   |       |       |       |
|---------------------|--|----------------|-------|-------|-------|---------------------|--|--------|-------|-------|-------|
|                     |  | Sector         |       |       |       |                     |  | Sector |       |       |       |
| Pollutant           |  | Elec           | Comm  | Res   | Ind   | Pollutant           |  | Elec   | Comm  | Res   | Ind   |
| CO                  |  | 0.014          | 0.015 | 0.015 | 0.014 | CO                  |  | 0.64   | 5.82  | 5.71  | 5.82  |
| VOCs                |  | 0.002          | 0.002 | 0.002 | 0.001 | VOCs                |  | 0.0006 | 0.094 | 1.312 | 0.094 |
| NO <sub>x</sub>     |  | 0.134          | 0.057 | 0.056 | 0.057 | NO <sub>x</sub>     |  | 0.07   | 0.64  | 0.07  | 0.64  |
| SO <sub>x</sub>     |  | 0.089          | 0.083 | 0.083 | 0.083 | SO <sub>x</sub>     |  | 0.004  | 0.032 | 0.032 | 0.032 |
| PM <sub>Total</sub> |  | 0.020          | 0.006 | 0.006 | 0.006 | PM <sub>Total</sub> |  | 0.34   | 3.08  | 3.08  | 3.08  |
| PM <sub>10</sub>    |  | 0.014          | 0.003 | 0.003 | 0.003 | PM <sub>10</sub>    |  | 0.33   | 2.77  | 2.77  | 2.77  |
| PM <sub>2.5</sub>   |  | 0.010          | 0.002 | 0.002 | 0.003 | PM <sub>2.5</sub>   |  | 0.26   | 2.34  | 2.34  | 2.34  |

|                 |  | Coal (Bituminous, Low Sulphur) |       |       |       |                 |  | Coal (Sub-Bituminous, Low Sulphur) |       |       |       |
|-----------------|--|--------------------------------|-------|-------|-------|-----------------|--|------------------------------------|-------|-------|-------|
|                 |  | Sector                         |       |       |       |                 |  | Sector                             |       |       |       |
| Pollutant       |  | Elec                           | Comm  | Res   | Ind   | Pollutant       |  | Elec                               | Comm  | Res   | Ind   |
| CO              |  | 0.008                          | 0.088 | 0.088 | 0.088 | CO              |  | 0.008                              | 0.008 | 0.008 | 0.008 |
| VOCs            |  | 0.001                          | 0.001 | 0.001 | 0.001 | VOCs            |  | 0.001                              | 0.001 | 0.001 | 0.001 |
| NO <sub>x</sub> |  | 0.197                          | 0.154 | 0.154 | 0.154 | NO <sub>x</sub> |  | 0.122                              | 0.122 | 0.122 | 0.122 |
| SO <sub>x</sub> |  | 0.202                          | 0.202 | 0.202 | 0.202 | SO <sub>x</sub> |  | 0.294                              | 0.294 | 0.294 | 0.294 |

|                           |       |       |       |       |                           |       |       |       |       |
|---------------------------|-------|-------|-------|-------|---------------------------|-------|-------|-------|-------|
| <b>PM<sub>Total</sub></b> | 0.833 | 0.305 | 0.305 | 0.305 | <b>PM<sub>Total</sub></b> | 0.654 | 0.654 | 0.654 | 0.654 |
| <b>PM<sub>10</sub></b>    | 0.599 | 0.217 | 0.217 | 0.217 | <b>PM<sub>10</sub></b>    | 0.470 | 0.470 | 0.470 | 0.470 |
| <b>PM<sub>2.5</sub></b>   | 0.156 | 0.054 | 0.054 | 0.054 | <b>PM<sub>2.5</sub></b>   | 0.123 | 0.123 | 0.123 | 0.123 |

**Table 2. National Average Sulphur and Ash Content of Fuels**

| <b>Liquid Fuels</b>     | <b>Average Sulphur Content (%wt.)</b> | <b>Average Ash Content (%wt.)</b> |
|-------------------------|---------------------------------------|-----------------------------------|
| Aviation Turbo Fuel     | .055                                  | —                                 |
| Motor/Aviation Gasoline | .032                                  | —                                 |
| Kerosene/Stove oil      | .045                                  | —                                 |
| Low-Sulphur Diesel Fuel | .032                                  | —                                 |
| Diesel Fuel             | .230                                  | —                                 |
| Light Fuel Oil          | .203                                  | —                                 |
| Heavy Fuel Oil          | 1.771                                 | —                                 |
| Plant Consumption       | 1.668                                 | —                                 |

| <b>Coal</b>   | <b>Average Sulphur Content (%wt.)</b> | <b>Average Ash Content (%wt.)</b> |
|---|---------------------------------------|-----------------------------------|
| <b>Western (B.C., Alberta, Saskatchewan and Manitoba)</b> |                                       |                                   |
| Anthracite  | 0.64                                  | 16.4                              |
| Lignite   | 0.41                                  | 15.7                              |
| Bituminous  | 0.47                                  | 15.8                              |
| Sub-bituminous  | 0.35                                  | 12.4                              |
| <b>Eastern (Ontario, Quebec, Atlantic Provinces)</b>      |                                       |                                   |
| Low sulphur bituminous                                    | 0.89                                  | 0.9                               |
| High sulphur bituminous                                   | 6.75                                  | 22.5                              |

## Appendix C

## CAC Calibration tables for Ontario

For calibration tables of other regions / sectors contact the author.

| <b>Residential</b> |                |             |             |             |                   |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>     | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                 | 211,305        | t           | 130,428     | t           | 38%               |
| VOCS               | 115,024        | t           | 29,355      | t           | 74%               |
| NOX                | 18,232         | t           | 17,396      | t           | 5%                |
| PM Tot             | 30,483         | t           | 17,731      | t           | 42%               |
| PM<2.5             | 29,729         | t           | 9,989       | t           | 66%               |
| PM<10              | 29,779         | t           | 17,599      | t           | 41%               |
| SOx                | 4,848          | t           | 4,328       | t           | 11%               |

| <b>SCALED CACS</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 211,305        | t           | 218,218     | t           | -3%               |
| VOCS               | 115,024        | t           | 98,330      | t           | 15%               |
| NO <sub>x</sub>    | 18,232         | t           | 17,396      | t           | 5%                |
| PM Tot             | 30,483         | t           | 26,596      | t           | 13%               |
| PM<2.5             | 29,729         | t           | 23,939      | t           | 19%               |
| PM<10              | 29,779         | t           | 26,399      | t           | 11%               |
| SO <sub>x</sub>    | 4,848          | t           | 4,328       | t           | 11%               |

| <b>Commercial</b> |                |             |             |             |                   |
|-------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>    | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                | 3,358          | t           | 6,253       | t           | -86%              |
| VOCS              | 1,244          | t           | 385         | t           | 69%               |
| NO <sub>x</sub>   | 11,942         | t           | 12,819      | t           | -7%               |
| PM Tot            | 1,070          | t           | 638         | t           | 40%               |
| PM<2.5            | 923            | t           | 570         | t           | 38%               |
| PM<10             | 976            | t           | 587         | t           | 40%               |
| SO <sub>x</sub>   | 29,800         | t           | 1,691       | t           | 43%               |

| <b>SCALED CACs</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 3,358          | t           | 3,335       | t           | 1%                |
| VOCS               | 1,244          | t           | 962         | t           | 23%               |
| NO <sub>x</sub>    | 11,942         | t           | 12,819      | t           | -7%               |
| PM Tot             | 1,070          | t           | 957         | t           | 11%               |
| PM<2.5             | 923            | t           | 855         | t           | 7%                |
| PM<10              | 976            | t           | 881         | t           | 10%               |
| SO <sub>x</sub>    | 2,980          | t           | 3,383       | t           | -14%              |

| <b>Electricity</b> |                |             |             |             |                   |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>     | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                 | 3,026          | t           | 6,228       | t           | -106%             |
| VOCS               | 311            | t           | 447         | t           | -44%              |
| NO <sub>x</sub>    | 59,399         | t           | 31,057      | t           | 48%               |
| PM Tot             | 5,797          | t           | 3,186       | t           | 45%               |
| PM<2.5             | 719            | t           | 1,056       | t           | -47%              |
| PM<10              | 1,680          | t           | 1,108       | t           | 34%               |
| SO <sub>x</sub>    | 74,730         | t           | 34,875      | t           | 53%               |

| <b>SCALED CACS</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 3,026          | t           | 3,679       | t           | -22%              |
| VOCS               | 311            | t           | 273         | t           | 12%               |
| NO <sub>x</sub>    | 59,399         | t           | 46,585      | t           | 22%               |
| PM Tot             | 5,797          | t           | 4,779       | t           | 18%               |
| PM<2.5             | 719            | t           | 739         | t           | -3%               |
| PM<10              | 1,680          | t           | 1,330       | t           | 21%               |
| SO <sub>x</sub>    | 74,730         | t           | 69,749      | t           | 7%                |

| <b>Metal Smelting and Refining</b> |                |             |             |             |                   |
|------------------------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>                     | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                                 | 164            | t           | 431         | t           | -163%             |
| VOCS                               | 31             | t           | 28          | t           | 9%                |
| NO <sub>x</sub>                    | 2,286          | t           | 1,010       | t           | 56%               |
| PM Tot                             | 9,070          | t           | 153,442     | t           | -1592%            |
| PM<2.5                             | 6,469          | t           | 21,355      | t           | -230%             |
| PM<10                              | 7,927          | t           | 127,673     | t           | -1511%            |
| SO <sub>x</sub>                    | 287,522        | t           | 234,753     | t           | 18%               |

| <b>SCALED CACS</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 164            | t           | 129         | t           | 21%               |
| VOCS               | 31             | t           | 28          | t           | 9%                |
| NO <sub>x</sub>    | 2,286          | t           | 2,020       | t           | 12%               |
| PM Tot             | 9,070          | t           | 10,952      | t           | -21%              |
| PM<2.5             | 6,469          | t           | 5,372       | t           | 17%               |
| PM<10              | 7,927          | t           | 9,051       | t           | -14%              |
| SO <sub>x</sub>    | 287,522        | t           | 234,750     | t           | 18%               |

| <b>Iron and Steel Production</b> |                |             |             |             |                   |
|----------------------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>                   | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                               | 720,434        | t           | 604,598     | t           | 16%               |
| VOCS                             | 27,710         | t           | 12,108      | t           | 56%               |
| NO <sub>x</sub>                  | 20,965         | t           | 24,532      | t           | -17%              |
| PM Tot                           | 16,264         | t           | 67,608      | t           | -316%             |
| PM<2.5                           | 5,267          | t           | 15,660      | t           | -197%             |
| PM<10                            | 7,998          | t           | 50,551      | t           | -532%             |
| SO <sub>x</sub>                  | 47,696         | t           | 44,320      | t           | 7%                |

| <b>SCALED CACs</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 720,434        | t           | 593,432     | t           | 18%               |
| VOCS               | 27,710         | t           | 21,736      | t           | 22%               |
| NO <sub>x</sub>    | 20,965         | t           | 24,417      | t           | -16%              |
| PM Tot             | 16,264         | t           | 12,776      | t           | 21%               |
| PM<2.5             | 5,267          | t           | 5,421       | t           | -3%               |
| PM<10              | 7,998          | t           | 8,924       | t           | -12%              |
| SO <sub>x</sub>    | 47,696         | t           | 44,320      | t           | 7%                |

| <b>Chemical Products Manufacturing</b> |                |             |             |             |                   |
|--|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>                         | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                                     | 16,811         | t           | 7,371       | t           | 56%               |
| VOCS                                   | 19,352         | t           | 5,089       | t           | 74%               |
| NO <sub>x</sub>                        | 9,945          | t           | 5,146       | t           | 48%               |
| PM Tot                                 | 3,706          | t           | 3,467       | t           | 6%                |
| PM<2.5                                 | 896            | t           | 253         | t           | 72%               |
| PM<10                                  | 1,598          | t           | 293         | t           | 82%               |
| SO <sub>x</sub>                        | 4,608          | t           | 1,933       | t           | 58%               |

| <b>SCALED CACs</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 16,811         | t           | 15,240      | t           | 9%                |
| VOCS               | 19,352         | t           | 15,633      | t           | 19%               |
| NO <sub>x</sub>    | 9,945          | t           | 10,735      | t           | -8%               |
| PM Tot             | 3,706          | t           | 2,882       | t           | 22%               |
| PM<2.5             | 896            | t           | 1,041       | t           | -16%              |
| PM<10              | 1,598          | t           | 1,248       | t           | 22%               |
| SO <sub>x</sub>    | 4,608          | t           | 3,838       | t           | 17%               |



| <b>Industrial Minerals</b> |                |             |             |             |                   |
|----------------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>             | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                         | 4,380          | t           | 3,746       | t           | 14%               |
| VOCS                       | 365            | t           | 368         | t           | -1%               |
| NO <sub>x</sub>            | 11,238         | t           | 17,045      | t           | -52%              |
| PM Tot                     | 8,556          | t           | 16,012      | t           | -87%              |
| PM<2.5                     | 2,216          | t           | 1,967       | t           | 11%               |
| PM<10                      | 4,073          | t           | 6,334       | t           | -56%              |
| SO <sub>x</sub>            | 20,840         | t           | 12,964      | t           | 38%               |

| <b>SCALED CACs</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 4,380          | t           | 3,438       | t           | 22%               |
| VOCS               | 365            | t           | 434         | t           | -19%              |
| NO <sub>x</sub>    | 11,238         | t           | 12,491      | t           | -11%              |
| PM Tot             | 8,556          | t           | 9,446       | t           | -10%              |
| PM<2.5             | 2,216          | t           | 1,785       | t           | 19%               |
| PM<10              | 4,073          | t           | 4,476       | t           | -10%              |
| SO <sub>x</sub>    | 20,840         | t           | 18,359      | t           | 12%               |

| <b>Mining</b>   |                |             |             |             |                   |
|-----------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>  | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO              | 21,893         | t           | 233         | t           | 99%               |
| VOCS            | 706            | t           | 10          | t           | 99%               |
| NO <sub>x</sub> | 2,294          | t           | 1,220       | t           | 47%               |
| PM Tot          | 38,487         | t           | 70,641      | t           | -84%              |
| PM<2.5          | 1,714          | t           | 33,975      | t           | -1882%            |
| PM<10           | 6,200          | t           | 68,052      | t           | -998%             |
| SO <sub>x</sub> | 45,680         | t           | 896         | t           | 98%               |

| <b>SCALED CACs</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 21,893         | t           | 22,606      | t           | -3%               |
| VOCS               | 706            | t           | 697         | t           | 1%                |
| NO <sub>x</sub>    | 2,294          | t           | 1,831       | t           | 20%               |
| PM Tot             | 38,487         | t           | 42,536      | t           | -11%              |
| PM<2.5             | 1,714          | t           | 1,780       | t           | -4%               |
| PM<10              | 6,200          | t           | 7,051       | t           | -14%              |
| SO <sub>x</sub>    | 45,680         | T           | 35,790      | t           | 22%               |

| <b>Pulp and Paper</b> |                |             |             |             |                   |
|-----------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>        | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                    | 28,356         | T           | 23,234      | t           | 18%               |
| VOCS                  | 9,477          | T           | 3,289       | t           | 65%               |
| NO <sub>x</sub>       | 9,959          | T           | 13,407      | t           | -35%              |
| PM Tot                | 19,277         | T           | 8,481       | t           | 56%               |
| PM<2.5                | 6,430          | T           | 5,596       | t           | 13%               |
| PM<10                 | 9,438          | T           | 6,796       | t           | 28%               |
| SO <sub>x</sub>       | 11,647         | T           | 14,606      | t           | -25%              |

| <b>SCALED CACs</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 28,356         | t           | 23,037      | t           | 19%               |
| VOCS               | 9,477          | t           | 8,199       | t           | 13%               |
| NO <sub>x</sub>    | 9,959          | t           | 10,992      | t           | -10%              |
| PM Tot             | 19,277         | t           | 16,829      | t           | 13%               |
| PM<2.5             | 6,430          | t           | 5,563       | t           | 13%               |
| PM<10              | 9,438          | t           | 10,128      | t           | -7%               |
| SO <sub>x</sub>    | 11,647         | t           | 14,125      | t           | -21%              |

| <b>Other Manufacturing</b> |                |             |             |             |                   |
|----------------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>             | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| CO                         | 20,321         | t           | 41,648      | t           | -105%             |
| VOCS                       | 45,778         | t           | 1,020       | t           | 98%               |
| NO <sub>x</sub>            | 28,173         | t           | 21,855      | t           | 22%               |
| PM Tot                     | 39,083         | t           | 20,739      | t           | 47%               |
| PM<2.5                     | 12,451         | t           | 14,914      | t           | -20%              |
| PM<10                      | 22,592         | t           | 18,416      | t           | 18%               |
| SO <sub>x</sub>            | 18,462         | t           | 10,185      | t           | 45%               |

| <b>SCALED CACs</b> | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|--------------------|----------------|-------------|-------------|-------------|-------------------|
| CO                 | 20,321         | t           | 20,824      | t           | -2%               |
| VOCS               | 45,778         | t           | 40,802      | t           | 11%               |
| NO <sub>x</sub>    | 28,173         | t           | 21,855      | t           | 22%               |
| PM Tot             | 39,083         | t           | 41,478      | t           | -6%               |
| PM<2.5             | 12,451         | t           | 14,914      | t           | -20%              |
| PM<10              | 22,592         | t           | 18,416      | t           | 18%               |
| SO <sub>x</sub>    | 18,462         | t           | 14,259      | t           | 23%               |

| <b>Petroleum Refining</b> |                |             |             |             |                   |
|---------------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>INITIAL</b>            | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
| <b>CO</b>                 | 4,711          | t           | 2,042       | t           | 57%               |
| <b>VOCS</b>               | 25,648         | t           | 17,654      | t           | 31%               |
| <b>NO<sub>x</sub></b>     | 12,822         | t           | 5,342       | t           | 58%               |
| <b>PM Tot</b>             | 2,894          | t           | 357         | t           | 88%               |
| <b>PM&lt;2.5</b>          | 1,314          | t           | 239         | t           | 82%               |
| <b>PM&lt;10</b>           | 2,176          | t           | 306         | t           | 86%               |
| <b>SO<sub>x</sub></b>     | 61,595         | t           | 9,405       | t           | 85%               |

| <b>SCALED CACs</b>    | <b>RDIS II</b> | <b>Unit</b> | <b>CIMS</b> | <b>Unit</b> | <b>Difference</b> |
|-----------------------|----------------|-------------|-------------|-------------|-------------------|
| <b>CO</b>             | 4,711          | t           | 5,106       | t           | -8%               |
| <b>VOCS</b>           | 25,648         | t           | 26,261      | t           | -2%               |
| <b>NO<sub>x</sub></b> | 12,822         | t           | 10,187      | t           | 21%               |
| <b>PM Tot</b>         | 2,894          | t           | 2,328       | t           | 20%               |
| <b>PM&lt;2.5</b>      | 1,314          | t           | 1,096       | t           | 17%               |
| <b>PM&lt;10</b>       | 2,176          | t           | 1,740       | t           | 20%               |
| <b>SO<sub>x</sub></b> | 61,595         | t           | 52,070      | t           | 15%               |