Hybrid modeling of industrial energy consumption and greenhouse gas emissions with an application to Canada

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Abstract

In this paper, we explore the implications for Canada’s industrial sector of an economy-wide, compulsory greenhouse gas reduction policy, such as a tax or emissions cap and tradable permits system. The model used in the analysis is CIMS, a hybrid energy-economy model that combines characteristics of the contrasting top-down and bottom-up approaches in order to generate useful information for policy makers. CIMS is technologically explicit, behaviorally realistic, and has the ability to model equilibrium feedbacks. However, each of these strengths is linked to challenges when it comes to forecasting the impact of greenhouse gas policy. We explore the strengths and weaknesses of CIMS, and provide results from simulating the response of the Canadian industrial sector to GHG charges implemented throughout the economy, starting in the year 2006 and extending to the year 2030.

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1. Introduction

There are a variety of reasons for modeling industrial energy consumption, among them a series of environmental and security externalities that make this category of consumption a potential target for public policy intervention. The focus of this paper is on the modeling of industrial energy consumption in order to forecast greenhouse gas (GHG) emissions caused by
the combustion of fossil fuel products.¹ We set out to answer the following question: if an economy-wide, compulsory GHG reduction policy, such as a GHG tax or emissions cap and tradable permits system were implemented in Canada, what would be the response of the industrial sector in terms of energy consumption and GHG emissions?

This CIMS model used in this analysis is a hybrid energy-economy model that combines characteristics of the bottom-up and top-down approaches in order to perform well in terms of three key criteria for determining usefulness to policy-makers: technological explicitness, behavioral realism, and the ability to capture equilibrium feedbacks. Each of these characteristics represents a strength of the modeling tool in terms of forecasting the impact of GHG policy on the Canadian industrial sector; however, each is also associated with one or more weaknesses. Technological explicitness allows CIMS to address technological change within industry and its response to policy in a way that top-down models cannot, but uncertainty with respect to the pace and direction of this change remains a problem. Behavioral realism is necessary for simulating the anticipated response to a GHG tax or cap and tradable emissions program. The downside to incorporating behavioral realism within a technologically explicit model is that considerable resources are required and parameter values remain uncertain. CIMS is an integrated, energy-economy equilibrium model; however, the extent of linkages and feedbacks is limited by the iterative process required to reach equilibrium.

We provide background on the conventional top-down and bottom-up paradigms used to model energy consumption and GHG emissions in response to policy in Section 2. In Section 3, we describe CIMS in terms of its characterization of industrial sector technologies, technology choice algorithm, incorporation of equilibrium feedbacks, and representation of endogenous technological change. In Section 4, we address the strengths and weaknesses of CIMS for GHG policy analysis. In Section 5, we provide results and discuss the impact of compulsory GHG reduction policy on energy consumption and GHG emissions in the Canadian industrial sector. Two examples of technology competitions are explored in detail, generating insights into how technology choices are made in CIMS.

2. Models for assessing the response to energy and GHG policy: the conventional bottom-up and top-down approaches

Historically, policy-makers have faced the dilemma of choosing between bottom-up and top-down models to assess policies to influence energy-related technology choices (Jaccard et al., 2003b). Bottom-up models show how changes in energy efficiency, fuel, emission control equipment, and infrastructure might influence energy use and thus environmental impacts (Morris et al., 2002). Technologies that provide the same energy service are generally assumed to be perfect substitutes except for differences in their anticipated financial costs, energy use, and emissions. When their financial costs in different time periods are converted into present value using a social discount rate, many technologies available for abating various emissions appear to be profitable or just slightly more expensive relative to existing stocks of equipment and buildings. Bottom-up models often show, therefore, that environmental improvement could be profitable or low-cost if these low-emission technologies were to achieve market dominance (Bailie et al., 2002). Traditional bottom-up models are partial-equilibrium models — focusing on optimization of costs within the energy sector or a specific subsector, but omitting linkages between these sectors and the wider economy.

¹ Process emissions linked to production levels rather than fuel consumption or technology type, such as the release of large quantities of carbon dioxide when limestone used in cement and lime production is calcined, are also important and are considered in our analysis.
Many economists criticize this approach, however, for its assumption that a single, anticipated estimate of financial cost, using the social discount rate, indicates the full social cost of technological change (Jaffe and Stavins, 1994). New technologies present greater risks, as do the longer paybacks associated with investments in energy efficiency, and some low-emission technologies are not perfect substitutes. In addition, the partial-equilibrium approach can obscure key feedbacks within the economy that would be better captured with a full-equilibrium approach. To the extent that they ignore some of these costs and feedbacks, bottom-up models may inadvertently prescribe inappropriate policies and technologies.

The alternative, top-down analysis, estimates aggregate relationships between the relative costs and market shares of energy and other inputs to the economy, and links these to sectoral and total economic output in a broader equilibrium framework. Parameters for top-down models that characterize the response of the model to a policy, including the elasticities of substitution (ESUB) and the autonomous energy efficiency improvement (AEEI), are estimated empirically from historical data when possible, and judgmentally estimated when historical data do not allow for empirical estimation (Bataille et al., 2006). To the extent that parameters are estimated from real market data, as energy prices and consumption changed historically, they are assumed to reveal the actual preferences of consumers and businesses. Because they lack technological detail, top-down models are restricted to simulations of financial policies, which increase the relative cost of a given input share. The magnitude of the financial signal necessary to achieve a given emission reduction target indicates its implicit cost, including the intangible costs related to the risks of new technologies, the risks of long payback technologies, and preferences for the attributes of one technology over its competitor. Thus, estimates of the cost of achieving an environmental goal obtained using a top-down model are usually higher and almost never lower than bottom-up estimates (Rivers and Jaccard, 2006).

The top-down approach is also vulnerable to the criticism of being unhelpful to policy-makers. If the critical top-down parameters for portraying technological change – ESUB and AEEI – are estimated from aggregate, historical data, there is no guarantee that these parameter values will remain valid into the future under different policies for environmental improvement (Grubb et al., 2002). Increasingly concerned with this problem, some top-down modelers are exploring ways of treating technological change endogenously. However, as of yet there has been little success in linking real-world evidence to the estimation of aggregate parameters of technological change in these models (Loschel, 2002). Another difficulty is that the constraints of policy development processes often push policy-makers towards technology- and building-specific policies in the form of tax credits, subsidies, regulations, and information programs. Because conventional top-down models represent technological change as an abstract, aggregate phenomenon, this approach only helps policy-makers assess economy-wide financial policies such as taxes and tradable permits.

While it is impossible for any policy model to be completely accurate in its representation of current conditions or its characterization of future dynamics, the above discussion suggests criteria by which we can judge the ability of a model to be more useful to policy-makers seeking to induce technological change. Policy-makers need models that can realistically evaluate the combined effect of policies that range from economy-wide to technology-specific, and these instruments will likely include command-and-control regulations as well as financial charges and subsidies. To do so, the models should include an explicit representation of technologies that compete to provide services throughout the economy, should simulate the way in which consumers, firms, and producers choose between these technologies in a way that closely reflects the real-world, and should capture equilibrium feedbacks between energy-technology decisions and the overall structure and performance of the economy.
Since neither conventional bottom-up nor top-down models perform well in relation to all three of these criteria, efforts have been made to develop hybrids that combine key elements of both types of models. Thus, some types of bottom-up models integrate energy supply and demand, and some even include interactions between the energy system and the economy as a whole. Developments with the MARKAL optimization model have been particularly noteworthy (Nystrom and Wene, 1999). A new variant of this model called SAGE introduces some degree of behavioral realism into the technology acquisition process (Loulou et al., 2004) by modeling consumers and producers as myopic and including a representation of non-monetary costs that influence behavior. On the other side, some top-down models include technological detail, mostly in the energy supply sector (Bohringer and Loeshel, 2006), although others have progressed further in including a detailed representation of other sectors (Schafer and Jacoby, 2006; Laitner and Hanson, 2006).

3. The CIMS hybrid modeling approach

The CIMS model used in this study has the technological richness of a bottom-up model, but simulates technology choices by firms and households using empirically estimated behavioral parameters instead of portraying these agents as financial cost optimizers. In addition, it integrates energy supply and demand, and includes links between energy and the entire economy.

3.1. Characterization of technologies

CIMS represents technologies explicitly in both its energy supply and energy demand components. The supply component includes submodels depicting the supply and delivery of electricity, natural gas, petroleum products, and coal. Energy demand includes the residential, industrial, commercial/institutional, and transportation sectors. Of the energy demand components, the industrial component is the most complex because of its heterogeneous processes and technologies. CIMS incorporates detailed representations of chemical products, industrial minerals, iron and steel, metal smelting, metals and mineral mining, other manufacturing, pulp and paper, and petroleum refining. In the Canadian version of CIMS used for this study, sectors and subsectors are represented within each of seven geographic regions.\(^2\)

\(^2\) These regions correspond to the Canadian provinces except that the Atlantic provinces are modeled together as one region, while the northern territories are included in British Columbia.
Each industrial submodel in CIMS has its own driving variable, usually expressing the total amount of final product produced or the amount of raw input processed (e.g., tonnes of steel, tonnes of mineral ore throughput, m$^3$ refined petroleum products). Initially, the driving variables are set exogenously, often based on official forecasts used by Natural Resources Canada, but they can adjust endogenously in response to policy.

The sequence of activities required to generate the final product of an industrial subsector is described in a process flow model, as illustrated in Fig. 1 for the iron and steel industry. A CIMS flow model is geared towards representing technology evolution and energy consumption rather than economic criteria (as in a top-down model where units are typically in monetary terms). The flow model represents process stages in which energy consumption can be distinctly estimated; hierarchical processes are linked by engineering ratios. Technology competitions take place at the lowest level nodes in the hierarchy, what we refer to as “energy service nodes” in CIMS.

Often, major process technologies have requirements for steam generation or other auxiliary energy services in addition to their direct fuel consumption. Auxiliary systems that supply these services fall into four general categories: steam generation systems (boilers and cogenerators); lighting; heating, ventilating, and air conditioning (HVAC) systems; and electric motor systems (motors and the pumps, fans, compressors, and conveyers driven by them). Generic steam and electric motor systems are described by a separate auxiliary process flow diagram (described in more detail below) and can be called upon by any of the industrial subsectors. Because the energy demands for lighting and HVAC tend to be relatively small, these services are usually linked directly to the specific process flow model for a subsector through ratios that estimate the amount of energy service required. Additional services that are specific to a particular industrial subsector

<table>
<thead>
<tr>
<th>Submodel</th>
<th>Major processes and products</th>
<th>Technology competitions</th>
<th>Technologies</th>
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<tr>
<td>Industrial minerals</td>
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<td>72</td>
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<tr>
<td>Pulp and paper</td>
<td>6</td>
<td>26</td>
<td>141</td>
</tr>
<tr>
<td>Petroleum refining</td>
<td>3</td>
<td>19</td>
<td>80</td>
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Table 1
Industrial submodel detail in CIMS

![Fig. 2. Process flow model for the other manufacturing industry.](image-url)
are represented in the flow model for that subsector, but by nodes that are outside of the main flow diagram (e.g., the oxygen, reheating, slab roughing, and slab finishing nodes in Fig. 1).

Representations of key technologies that are able to satisfy a given energy service demand are incorporated into the industrial submodels of CIMS, including new technologies that may not yet have achieved significant market penetration. For example, referring to Fig. 1, there are several different configurations of basic oxygen furnace (BOF), which consume different fuel types, have different waste gas recovery rates, different energy efficiencies, and different costs. Table 1 shows the approximate level of detail in each industrial submodel of CIMS in Canada in terms of the number of major processes and products, technology competitions, and technologies represented.

The CIMS submodel representing other manufacturing industries includes those industries which do not consume enough energy to merit the development of a separate model (e.g., food manufacturing, textiles). Because of the variety of technologies and processes involved, a simplified flow model of generic energy services is used to represent the aggregate energy consumption of these industries, as shown in Fig. 2. As there is no single product which dominates the production processes and to which the production of all other products may be linked, the driving variable of the other manufacturing submodel is expressed in monetary terms such as the real domestic product of the industry.

Motor and steam auxiliary systems that are common across industry are represented by the generic flow model depicted in Fig. 3. CIMS models six auxiliary groups related to electric motor systems: pumps, fans, compressors, and conveyers demand shaft or mechanical drive provided by motors, while certain process technologies require direct drive output. Table 2 shows the number of technologies represented in CIMS by auxiliary technology class.

In terms of technical and financial characteristics, equipment is represented in CIMS in a way that is similar to a bottom-up model. CIMS contains data on the initial market shares of equipment stocks in a base year (currently 2000). Individual technologies are described by their capacity,
capital cost, unit energy consumption (and output for energy conversion equipment), non-energy operating cost, emissions, expected lifetime, and first year of market availability (for new technologies). Process emissions linked to production levels rather than technology type or fuel consumption are also represented.

The original source for data on industrial technologies in CIMS was the Industrial Sector Technology Use Model (ISTUM) developed by the US Department of Energy (1983).4 These data were significantly updated at Simon Fraser University in the mid to late 1990s to create the Intra-Sectoral Technology Use Model (also called ISTUM) (Nyboer, 1997). There are various additional sources for the current CIMS technology database, including public statistical agencies, energy utilities, literature reviews, industry associations, surveys of sector experts, and a comprehensive review as part of Canada’s National Climate Change Process in 1999–2000. Because there are few detailed surveys of the annual energy consumption of the individual capital stocks tracked by the model (especially smaller units), these must be estimated from surveys at different levels of technological detail and by calibrating the model’s simulated energy consumption to real-world aggregate data.

CIMS uses a capital stock vintaging framework, where technologies are retired according to an age-dependent function, and new technologies fill the gap between service demand and existing capital stock in each five-year period of the simulation. Such a formulation is especially important in the industrial sector, where long-lived capital stocks cause significant inertia in energy consumption and GHG emissions. CIMS allows retrofits of some industrial sector technologies, but unlike some technologically detailed models (e.g., MARKAL, NEMS), does not allow the life of a technology to be extended through investments in upgrading or maintenance.

### 3.2. Technology choice

CIMS simulates the competition of technologies at each energy service node based on a comparison of their life cycle costs (LCCs) and some technology-specific controls, such as a maximum market share limit in the cases where a technology’s market share is constrained by physical, technical, or regulatory factors. CIMS applies a definition of LCC that includes intangible costs representing consumer and business preferences and the implicit discount rates

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3 Technology and energy costs in CIMS are expressed in $1995 Canadian dollars.
4 Jaccard and Roop (1990) describe the early evolution of ISTUM.
revealed by real-world technology acquisition behavior. Eq. (1) describes how CIMS determines technology market shares for new capital stocks.

\[
MS_j = \frac{\left[ CC_j \frac{r}{1-(1+r)^{-1}} + OC_j + EC_j + ij \right]^{-v}}{\sum_{k=1}^{k} \left[ CC_k \frac{r}{1-(1+r)^{-1}} + OC_k + EC_k + ik \right]^{-v}}
\]

* MS<sub>j</sub> is the market share of technology <i>j</i>, CC<sub>j</sub> is its capital cost, OC<sub>j</sub> is its maintenance and operation cost (labor), EC<sub>j</sub> is its energy cost, which depends on energy prices and energy consumption per unit of energy service output — producing a tonne of cold rolled steel, a liter of light fuel oil, or a tonne of paperboard. The <i>r</i> parameter represents the weighted average time preference of decision makers; it is the same for all technologies at a given energy service node, but can differ between nodes according to empirical evidence. The <i>ij</i> parameter represents all other intangible costs and benefits that consumers and businesses perceive, additional to the simple financial cost values used in most bottom-up analyses, for technology <i>j</i> as compared to all other technologies <i>k</i> at a given energy service node. <i>nj</i> is the lifetime of the technology in question.

The <i>v</i> parameter represents the heterogeneity in the market, whereby different consumers and businesses experience different LCCs. It determines the shape of the inverse power function that allocates market share to technology <i>j</i>. A high value of <i>v</i> means that the technology with the lowest LCC captures almost the entire new market share. A low value for <i>v</i> means that the market shares of new equipment are distributed fairly evenly, even if their LCCs differ significantly. Without defining constraints, a traditional linear programming optimization model would have <i>v</i> = ∞, equivalent to a step function where the cheapest technology captures 100% of the market.

For the industrial sector, the three key behavioral parameters in CIMS — <i>i</i>, <i>r</i>, and <i>v</i> — are estimated through a combination of literature review, judgment, meta-analysis, and discrete choice surveys (Rivers and Jaccard, 2005). Throughout most of the industrial sector, the discount rate for technology choice is set at 30% for non-discretionary technologies (major industrial processes) and at 50% for discretionary technologies (auxiliary technologies), retrofits, and any other technologies. These settings are based on the effective discount rates revealed from market data, which in turn are indicated by the rates of return that firms seem to require before acquiring new technologies of higher energy efficiency. The discount rate applied to process technologies in CIMS is consistent with research published by Hassett and Metcalf (1993), while the rate applied to auxiliary technologies is consistent with DeCanio (1993). We set the <i>v</i> parameter at 10 for most technology choices; when <i>v</i> is set at this level a competition between technology A and technology B will result in technology B capturing 85% of the market if technology A is 15% more expensive. Generally the <i>i</i> parameter is used to calibrate simulated market shares to revealed market data.

### 3.3. Equilibrium feedbacks

CIMS estimates the effect of a policy by comparing a reference case market equilibrium with one generated by a policy. The model operates by iteration of two sequential phases in each five-year period, with as many iterations as necessary to arrive at a new policy equilibrium in each period (as described by Bataille et al., 2006). In the first phase, an energy policy is applied to the energy demand sectors of the economy. Goods and services producers in the industrial submodels, and consumers in the other energy demand models choose capital stocks based on
CIMS’ technology choice algorithm, taking into account financial and intangible expenditure on capital, labor, energy, and emissions charges based on an initial set of input prices. Based on this, the model then calculates the demand and cost of delivery for electricity, refined petroleum goods, and primary energy commodities, including any policy effects. If the cost of producing any of these commodities has changed by a threshold amount from the reference case, the model is considered to be in disequilibrium and re-runs based on prices calculated from the new costs of production. The model iterates automatically until a new equilibrium set of energy prices and demands is reached. Fig. 4 provides a schematic of how this process occurs in each geographic region. An energy trade component, based on Armington price elasticities applied to changes in the cost of producing energy commodities, can be included to adjust trade in energy commodities in this first phase.

In the second phase, once a new equilibrium set of energy prices and demands under policy has been reached, the model calculates the degree to which the costs of producing traded goods and services have changed; assuming perfectly competitive markets, these changes translate directly into prices. For internationally traded goods, CIMS adjusts demand using Armington price elasticities that provide a long-run demand response that blends domestic and international demand for these goods.\(^5\) For example, an increase in the cost of production of pulp and paper, caused by paying a GHG tax, purchasing tradable permits for GHG emissions, or investing in GHG abatement, would lead to some reduction in output from that sector if the Armington price elasticity has a positive value. If demand for any good or service has shifted more than a threshold amount, the model is considered to be in disequilibrium and the energy supply and final demand phases are re-run using the last set of prices and demands. The model continues re-iterating until

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\(^5\) CIMS’ Armington elasticities are derived from Wirjanto (1999), who econometrically estimated them based on data from 1960–1990. If a policy were to generate a response outside the 1960–1990 historical experience, it may be desirable to set these elasticities judgmentally.
supply and demand for all goods and services come to a new equilibrium and repeats this convergence procedure in each subsequent five-year period of a complete run.

3.4. Endogenous technological change

CIMS includes two functions for simulating endogenous change in individual technologies’ characteristics in response to policy: a declining capital cost function and a declining intangible cost function. The declining capital cost function links a technology’s financial cost in future periods to its cumulative production, reflecting economies-of-learning and scale. The declining intangible cost function links the intangible costs of a technology in a given period with its market share in the previous period, reflecting improved availability of information and decreased perceptions of risk as new technologies become more broadly adopted. Attraction to a new technology can increase as its market share increases and information about its performance becomes more available (Banerjee, 1992; Arthur, 1989). Although the endogenous technological change functions are used throughout the residential, transportation, and electricity generation sectors, we have not incorporated them into the industrial components of the CIMS model, except for a few isolated technologies. In future work, we plan to expand this method of simulating endogenous technological change in the industrial sector.

4. Strengths and weaknesses of the CIMS method

CIMS combines the strengths of the top-down and bottom-up approaches in order to fulfill three key modeling criteria: technological explicitness, behavioral realism, and the ability to capture equilibrium feedbacks. While we believe that the strengths of this modeling approach outweigh the weaknesses, each of the main strengths of CIMS is associated with one or more weaknesses when it comes to answering the question posed by this analysis.

4.1. Technological explicitness

A key strength of CIMS is that it allows the modeler to explicitly recognize that the future mix of available technologies may differ fundamentally from that of the past. If applied over the long-term, a GHG tax or emissions trading scheme could influence technological change, including the costs associated with low-GHG technologies, thereby increasing the economy’s ability to reduce GHG emissions. Until recently, there was no incentive to design and commercialize such technologies. Now, they are under development worldwide and as research, development, and production expand, economies-of-scale and economies-of-learning reduce financial costs and can reduce the risks associated with new technologies (Azar and Dowlatabadi, 1999; Grubler et al., 1999).

Because CIMS is technologically explicit, we can incorporate into the model technologies that are currently only in the development stage, but that we expect might be commercialized, especially under a sustained and compulsory policy aimed at reducing GHG emissions. Explicitly tracking alternative technologies is particularly important in the industrial sector, where the potential exists for large, discrete jumps in types of technologies. For example, Mathiesen and Maestad (2004) show how failure to explicitly account for alternative steel refining technologies can lead to incorrect conclusions about international competitiveness when GHG policies are implemented. CIMS also has the ability, through the declining capital cost function, to represent how the cost of recently introduced low-GHG technologies might fall under a policy regime that causes their cumulative production to increase from what it otherwise
would have been. Capital cost decreases would then lead to further increases in cumulative production, and so on.

These features are in contrast to conventional top-down models, which have been used in the past to simulate economy-wide policy instruments like taxes and tradable permits. Technological change in these models is represented by parameters estimated from aggregate historical data, and may not be relevant in a carbon-constrained future.

Although the technologically explicit nature of CIMS allows us to represent technological change in response to policy in a way that most top-down models cannot, this aspect of CIMS also introduces an important weakness because of uncertainty about the pace and direction of technological change, including how technological change is affected by policy. CIMS represents energy efficiency and GHG intensity improvements in terms of the real or anticipated technology options that are available for meeting energy service demands. It does not contain an endogenous representation of the feedback effects of research and development. Over a longer simulation period it is not always possible to anticipate future new technology options or process improvements, and technological options can become exhausted before the end of the simulation. Although in some cases it is legitimate to assume that new technological developments will not occur because industries have reached practical limits in terms of improving process efficiency, in other cases this limitation of CIMS may under-represent the true potential for technological change in a GHG-constrained economy.

There is also the potential for technological change to evolve in the other direction, as a result of the development and marketing of new energy products and services that did not exist before. Such changes could result in increases in energy consumption and GHG emissions from the industrial sectors that provide raw materials or that manufacture such products. Again, it is not possible to anticipate such developments with accuracy in advance, especially as simulations extend further into the future. Thirty years ago we would not have predicted the impact of the personal computer and the sport utility vehicle on energy consumption and GHG emissions today. As a result of this uncertainty about future market evolution, our modeling may produce a reference case that is too low in terms of its energy consumption and GHG emissions forecasts for industry. This would in turn imply greater difficulty in achieving a target level of energy consumption or emissions under GHG policy than what our modeling would indicate.

Top-down models, with their parameters estimated from real market data, implicitly assume that the impact of technological change on energy consumption and GHG emissions will be similar in the future to what it was in the past, thereby avoiding the problem of knowing the exact nature of the new products and services involved. In our most recent research work, we are applying historical and emerging energy service demand data to estimate CIMS parameters that address the innovation and adoption of new technologies and services over time.

4.2. Behavioral realism

The technology choice algorithm of CIMS takes into account implicit discount rates revealed by real-world technology acquisition behavior, intangible costs that reflect consumer and business preferences, and heterogeneity in the marketplace. Because these factors are included in the market share equation along with the financial costs of technologies, CIMS can be categorized as a behavioral simulation model — the type of model that is critical for estimating the micro-economic response to policy given the realities of firm and household decision making.

By incorporating behavioral realism, the goal with CIMS is to be a more useful tool for policymakers to predict the effect of their policies. However, incorporating preferences at a detailed
level into a model that is technologically explicit requires considerable resources—a factor which may explain in part the limited development of this type of hybrid model. One of the few models operating at this level of technological and behavioral detail, the NEMS model of the US government, requires a staff of about 40 for upkeep and application.

In addition to the sheer volume of the data requirements, the non-financial preferences of consumers and firms are difficult to estimate. Economists use various methods of discrete choice analysis to estimate preferences for different technologies. Existing market data can elicit revealed preferences, while direct surveys can elicit stated preferences. Jaccard (2005) explains the limitations of revealed preference methods which have led researchers to focus on stated preference surveys in recent years to elicit behavioral parameters for CIMS, but notes that there are problems associated with this methodology as well. Currently, we are investigating the potential to combine revealed preference data with stated preference data where feasible. One of the main areas of focus of this work is on the behavioral influences affecting the choice of steam generation technology within the industrial sector.

The complexities associated with estimating behavioral parameters, combined with the fact that information cannot be collected for all the technology competitions in CIMS, result in a high degree of uncertainty associated with these parameters overall. The potential for preference change is also a key uncertainty. While additional research will help to improve our understanding of preferences and our predictive abilities, the long-term evolution of preferences will remain highly uncertain. Because of this inherent uncertainty, sensitivity testing of CIMS’ behavioral parameters is an important part of its use as a model for policy analysis.

4.3. Ability to capture equilibrium feedbacks

When an economy-wide GHG tax or emissions cap and tradable permits system imposes a significant regulatory constraint or financial penalty on emissions, we can expect that the interaction of energy supply and demand as well as the overall structure and performance of the economy may be affected as high cost actions are taken. CIMS is an integrated, energy-economy equilibrium model that simulates the interaction of energy supply-demand and the macroeconomic performance of the economy, including trade effects. Because we will be examining policies that impose medium to high costs on GHG emissions, it is essential for the modeling methodology to take these linkages into account. We will provide further details on the effect of these linkages on the industrial sector in our results section.

Unlike most computable general equilibrium models, the current version of CIMS does not equilibrate government budgets and the markets for employment and investment. Also, its representation of the economy’s inputs and outputs is skewed toward energy supply, energy intensive industries, and key energy end-uses in the residential, commercial/institutional, and transportation sectors. As such, CIMS does not capture some of the important feedbacks that could influence the response of Canada’s industrial sector to GHG policies that cause significant shifts in the cost of production for certain sectors. Work is underway to improve the ability to model important additional structural effects in CIMS by soft or hardlinking to a computable general equilibrium model.

Macroeconomic impacts depend in part on the position of Canada’s industry relative to those of its major competitors, an important consideration for both domestic demand and exports. The relationship with the US is especially critical for Canada because of strong trade links. As a result, when modeling the impact of climate policy on the Canadian industrial sector, it is necessary to make some general assumptions about what initiatives, if any, are being taken in the US and
elsewhere. When the Armington elasticity values in CIMS are activated, the implicit assumption is that Canada is acting alone in applying a cost to GHG emissions. It is unlikely, however, that Canada would impose a significant constraint or financial penalty on emissions in the absence of US action. An integrated model of the US and Canada is being constructed within the CIMS framework to simulate the effect of similar or slightly divergent policies in both countries.

Although we have discussed our efforts to incorporate additional linkages and feedbacks into CIMS, the extent of these improvements will ultimately be limited by the iterative nature of the model. CIMS’ equilibrium solution is found by first iterating between energy supply and energy demand, and then between these components and the macroeconomic module. Changes in energy demand can result in changes in energy supply, and consequently adjustments to energy prices, which in turn require rerunning of energy demand. Once energy supply and demand have reached equilibrium, production cost changes may result in a further adjustment to demand for traded goods and services at the macroeconomic level, requiring further iteration using these new demands. Given this simulation protocol, as more linked systems are integrated in a model like CIMS it becomes more difficult to reach an equilibrium solution (Jaccard et al., 2003a). As we expand the model’s application and linkage to other countries, we are exploring alternative solving algorithms to address this limitation.

5. Application to the Canadian industrial sector: the response to economy-wide GHG policy

We simulated the response of the Canadian industrial sector to an economy-wide, compulsory GHG reduction policy by testing GHG charges of $50 and $150/tonne CO$_2$e in CIMS. When a GHG charge is applied within CIMS, the results of the simulation are representative of the response to either a GHG tax, or to an emissions cap and tradable permits system in which permits trade at a price equivalent to the GHG charge (and aggregate emissions are capped at the levels reached during the run). Under GHG taxes and tradable permit schemes, it is possible to achieve an overall level of emission reduction at the minimum cost to society if each plant or household pursues abatement options only to the point where additional reductions cost more than paying the tax or purchasing an emission permit.

GHG charges of $50 and $150/tonne CO$_2$e were chosen to represent a medium and a high level, respectively, of financial constraint on GHG emissions. During the National Climate Change Process, the marginal cost of Canada achieving its entire Kyoto target starting in 2000 from domestic emission reductions was estimated to be $50/tonne CO$_2$e by MARKAL, a bottom-up linear programming model, and $150/tonne CO$_2$e by the CIMS hybrid model (Jaccard et al., 2003a). The marginal costs estimated by these two contrasting models provide a reasonable range for testing GHG charges in CIMS. We did not test charges below $50/tonne CO$_2$e because this level of financial constraint is insufficient for stimulating deep emission reductions.

In this section, we compare energy consumption and GHG emissions under the two GHG charge simulations to results obtained under a reference case forecast where emissions were not constrained by policy. Examples of two specific technology competitions are also provided to

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6. GHG charges are expressed in $1995 Canadian dollars. CO$_2$e stands for carbon dioxide equivalent, which converts all GHGs into units of carbon dioxide in terms of their greenhouse gas effect.

7. Jaccard et al. (2003a) reports a marginal cost from CIMS of $120/tonne CO$_2$e; however, this estimate increased as CIMS modelers corrected for missing intangible costs related to consumer preferences in some of the data provided by the National Climate Change Process, especially in the personal transportation sector.
illustrate the function of the technology choice algorithm in CIMS and to show how technological change was affected by the GHG charges in this analysis. For the simulations reported here, GHG charges were implemented in the year 2006, and the simulation extended to 2030 (the default simulation period for CIMS). To generate the results, equilibrium feedbacks were fully activated, with the exception of energy trade.8

5.1. Changes in energy consumption and GHG emissions

The GHG charges described above were applied across all of the energy demand and energy supply sectors modeled in CIMS, causing energy prices to increase based on their GHG content. Although electricity prices were not adjusted at the point of end-use, the feedbacks that exist between energy supply and demand in CIMS resulted in electricity price increases in the $150

8 While the quantities produced of all energy commodities were set using demand and supply balancing, endogenous pricing was used only for electricity and refined petroleum products; natural gas, crude oil, and coal prices remained at reference case levels (despite changes in the prices of electricity and petroleum products).
GHG charge simulation of more than 100% in regions that burn fossil fuels for generation. These increases were due to higher costs within the electricity generation sector, both as a result of actions taken to reduce GHG emissions, and as a result of the GHG charges associated with emissions that continued to occur.

Fig. 5 illustrates changes in energy consumption by industry, as forecast by CIMS under the GHG charges. As expected, percentage changes were greater under the $150 GHG charge than under the $50 GHG charge. In general, refined petroleum products, coal, and natural gas consumption decreased, while electricity consumption increased. These results reflect a switch from more carbon-intensive fuels to less carbon-intensive fuels, but were also affected by improvements in energy efficiency and by the final demand feedbacks in CIMS. Together, the latter two factors led to decreases in total energy consumption of 2 to 3% in the $50/tonne CO$_2$e simulation and 7 to 8% in the $150/tonne CO$_2$e simulation. Percentage changes tended to become more pronounced over time, as capital stock turnover provided additional opportunities for emission reduction. In 2010, electricity consumption decreased as the GHG charges caused increases in the price of this energy form. Over the course of the simulation, however, capital stock turnover presented opportunities for GHG reduction within the electricity generation sector at a cost less than the level of the GHG charge. The costs borne by the sector were therefore reduced, leading to smaller increases in electricity prices and increased electricity consumption in 2020 and 2030.

Direct GHG emissions from the Canadian industrial sector in the reference case, as well as under the two GHG charge scenarios are shown in Fig. 6.9 With GHG emissions priced at $50/tonne CO$_2$e, CIMS forecast a reduction in emissions of 14% or 22 Mt CO$_2$e by the end of the simulation period. At $150/tonne CO$_2$e, a reduction of 31% or 50 Mt CO$_2$e was achieved. Emission reductions in industry are limited by two factors. First, firms are more likely than households and even commercial tenants to have already pursued cost-effective options to reduce energy consumption. Thus, there is less additional potential to acquire equipment that cost-effectively improves energy efficiency or switches fuels. Second, some sectors are physically limited in their ability to reduce energy use. This inability may be because of minimum thermal requirements of industrial processes (ore refining, pulp production, etc.) or because of minimum energy requirements of generic mechanical energy uses such as conveyance, fans, and blowers.

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9 Direct GHG emissions include only emissions generated at the point of end-use. Emissions associated with generating and supplying various forms of energy (including electricity) are not accounted for.
The largest contributors to industrial GHG emission reductions were the industrial minerals, other manufacturing, pulp and paper, and petroleum refining subsectors. These subsectors together were responsible for a large percentage – in the range of 80 to 85% – of the total emission reductions reported for industry. Fig. 7 breaks down the emission reductions described by Fig. 6 according to each of the four key subsectors listed above; the contribution of the remaining sectors is shown in aggregate.

Emissions were reduced in the GHG charge simulations as a result of energy efficiency improvements, switching from more carbon-intensive fuels to less carbon-intensive fuels, and some structural change in the economy. We describe the role of these macroeconomic feedbacks first. Table 3 reports percentage changes in demand relative to the reference case for the industry subsectors that contributed most to direct emission reductions. For the GHG charges simulated, final demand feedbacks were 5% or lower for other manufacturing and pulp and paper, and remained below 10% for petroleum refining. Overall, the reductions in demand did not dominate the response of industry to the GHG charges.

The change reported for the petroleum refining sector is in fact a result of the interaction between supply and demand within CIMS, not final demand feedbacks.
The cement industry, housed within the industrial minerals submodel, was the exception in that it was particularly affected by final demand feedbacks. The industrial minerals subsector shrank by almost 50% under a GHG charge of $150/tonne CO$_2$e. Cement production, with its high heat requirements and significant process emissions, saw costs increase sharply under the GHG charges. Demand for domestically produced cement is very elastic in CIMS, and the production cost increases translated into substantial declines in demand. Policy-makers considering implementation of a GHG tax or an aggressive emissions cap and permit trading regime in Canada might be pressured to incorporate exemptive provisions for the cement industry if the US does not enact a similar policy.

Actions to reduce the GHG intensity of production include energy efficiency improvements and shifts to less carbon-intensive fuels. Reductions in the industrial minerals subsector, which includes cement, occurred due to changes in efficiency and the use of alternative fuels in process equipment (e.g., the installation of new higher-efficiency kilns). Within the other manufacturing subsector, significant fuel switching and numerous but small energy efficiency improvements were simulated to occur. The pulp and paper subsector has a large demand for process heat, and the emission reductions in this subsector resulted primarily from a switch away from carbon-intensive fuels towards greater use of wood waste and natural gas. Emission reductions also occurred from the selection of more efficient process equipment that reduced process heat requirements (e.g., the adoption of high intensity dryers in paper mills), and from improvements to boilers. Reductions in the GHG intensity of production within the petroleum refining subsector were primarily the result of actions that reduced the demand for direct process heat and process steam, and from actions that reduced the consumption of petroleum coke and increased the consumption of electricity.

Although we report only the direct GHG emission reductions by industry in this analysis, actions that reduce indirect emissions also occurred. This is because the GHG charges led to electricity price increases, which in turn encouraged actions such as increases in the efficiency of electric motor systems. These actions did not contribute to direct emission reductions, but they resulted in a diminished demand for electricity, which translated into indirect emission reductions accounted for within the electricity supply model. The increased penetration of cogeneration is another example of an action that occurred under the GHG charges because it reduced indirect emissions. In fact, direct emissions from industry can increase as a result of a shift to cogeneration. This action was especially strong in the pulp and paper subsector, where wood waste is available as a fuel source.

<table>
<thead>
<tr>
<th>Subsector</th>
<th>$50/tonne CO$_2$e</th>
<th>$150/tonne CO$_2$e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial minerals</td>
<td>18%</td>
<td>48%</td>
</tr>
<tr>
<td>Other manufacturing</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Pulp and paper</td>
<td>2%</td>
<td>5%</td>
</tr>
<tr>
<td>Petroleum refining</td>
<td>4%</td>
<td>9%</td>
</tr>
</tbody>
</table>

11 Results are only shown for the year 2020, as demand changes in other years did not deviate greatly from 2020 levels. Although capital stock turnover provided additional opportunities for emission reduction as the simulation progressed (dampening production cost increases), this was compensated for by growth in emissions under reference case conditions.
12 The effect of final demand feedbacks on the cement industry was limited to 50% in this study due to uncertainty surrounding the Armington elasticities used in CIMS when GHG emissions are priced as high as $150/tonne CO$_2$e.
13 Cogeneration simultaneously produces high-temperature heat and electricity. This technology can achieve system energy efficiency above 80%, far exceeding the efficiency of stand-alone thermal electricity plants.
5.2. Technology competition outcomes

Here we provide examples of two simulated technology competitions to illustrate the operation of the technology choice algorithm in CIMS. We examine the competition that occurs at the hot water boiler node in the other manufacturing submodel and the competition between technologies for aluminum electrolysis within the metal smelting submodel. The first example represents technologies that supply an auxiliary energy service to major process equipment; it demonstrates the influence of the behavioral parameters in CIMS. The second example represents technologies at a process node and highlights the uncertainty associated with forecasting technological change.

At the hot water boiler node in the other manufacturing submodel nine different technologies compete: natural gas, electricity, and oil boilers are each available in standard, efficient, and high efficiency models. In the reference case, efficient models captured the greatest portion of the market across fuel types. High efficiency models accounted for only a small fraction of the market due to their high costs, and this fraction did not increase significantly under the GHG charges. Therefore, the key action at this node was not an improvement in energy efficiency, but a switch from natural gas boilers to electric boilers (oil is only used where there is no access to natural gas).

Table 4 shows the new market shares simulated for electric boilers. These boilers have a lifetime of only nine years; as a result technology stock turnover was not an important factor and total market shares (incorporating new and existing stocks) converged to the new market shares relatively quickly. With the application of the GHG charges, electric boilers became the dominant technology but did not take over the entire market due to the effect of the heterogeneity parameter. Despite this resistance to change, the model was sensitive enough to show a decisive shift towards electric boilers under the $150 GHG charge. Market shares for the electric boilers increased over the simulation period due to energy price changes. Energy prices represent a large portion of the cost differences between technologies at this node, and as a result market shares are sensitive to changes in these prices.

In the section on strengths and weaknesses of CIMS, we discussed the uncertainty associated with estimation of behavioral parameters for the model. The technology competition outcome at the hot water boiler node might have been different if different values for the market heterogeneity ($v$) and time preference ($r$) parameters had been chosen. A simulation with a $v$ parameter value higher than the default of 10 would have allocated a greater market share to the technology with the lowest life cycle cost calculated according to Eq. (1) — natural gas boilers in the reference case and electric boilers (generally speaking) under the GHG charges. A lower $v$ parameter would have had the opposite effect, making the model less sensitive to the application of a GHG charge.

Changes in the time preference parameter would not have had a large impact on the market shares shown in Table 4, because capital costs of the hot water boilers do not vary much based on the type of energy used. The trade-off between up-front costs and ongoing costs is not paramount in the choice between boilers using alternative forms of energy. Changes in the value of $r$ would,

<table>
<thead>
<tr>
<th>New market share for electric hot water boilers in other manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>2010</td>
</tr>
<tr>
<td>2020</td>
</tr>
<tr>
<td>2030</td>
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</tbody>
</table>
however, have had an effect on the market penetration of the high efficiency boilers, as these
technologies deliver savings in energy costs over time in return for a greater capital cost
investment. A lower value of \( r \) would have resulted in a higher market share for the more efficient
technologies, especially under the GHG charges.

A strength of the technologically explicit nature of CIMS is that it allows the modeler to
simulate market penetration of low-GHG technologies that are still in the development stage. At
the aluminum electrolysis node within the metal smelting submodel, the inert anode, wetted
cathode option is assumed to be available in the year 2015. Wetted cathodes allow for decreased
anode-cathode distances, resulting in reduced electricity consumption, while inert anodes
eliminate GHG emissions associated with the production of primary aluminum and with anode
manufacture. The simulated market penetration of this technology is illustrated in Table 5 for the
province of Québec, the dominant region in Canada for aluminum production. Although new
market shares reached fairly high levels by the year 2020, the full effect was not reflected in the
total market shares shown in the lower part of the table. Capital stock turnover was slower at this
node than at the hot water boiler node because the lifetimes of aluminum electrolysis technologies
are set at 30 years in CIMS.

The technology competition results shown in Table 5 highlight some of the uncertainties
associated with forecasting technological change. The inert anode, wetted cathode combination
achieved significant market penetration almost immediately once it was commercially available,
even without the application of a financial penalty or regulated constraint on GHG emissions.
However, there is uncertainty as to whether this technology will actually be available in 2015.
Another source of uncertainty is that some analysts predict that the superior attributes of the inert
anode, wetted cathode option will result in almost complete dominance as soon as it is available. This
would suggest a higher value of \( v \) would be appropriate at this node, rather than the default of 10.

6. Conclusions

In forecasting the impact of an economy-wide, compulsory GHG reduction policy on energy
consumption and GHG emissions from the Canadian industrial sector, the CIMS hybrid energy-
economy model brings advantages associated with combining key attributes of the top-down and
bottom-up modeling paradigms. CIMS displays strengths in terms of its technological explicitness, behavioral realism, and ability to capture equilibrium feedbacks. However, each of these strengths is linked to one or more weaknesses; some these can be addressed in future work, while others must simply be kept in mind when interpreting the results.
Because it contains representations of the specific options available for reducing GHG emissions, CIMS can address technological change within industry and its response to policy in a way that top-down models cannot. The model is able to show the accelerated market penetration of low-GHG technologies, even technologies not currently on the market, in the event of a financial penalty or regulated constraint on GHG emissions. It is also possible, through the declining capital cost function of CIMS, to endogenously simulate the influence of GHG policy on the costs of new technologies that assist in emission reduction. Despite these strengths, uncertainty with respect to the pace and direction of technological change remains a problem. In fact, this category of uncertainty exists in all energy-economy models, but is illuminated in a technologically detailed model like CIMS; care must be taken to ensure that the technological options available over a given simulation period are as representative as possible.

The CIMS technology simulation algorithm takes into account not only the financial costs of technologies, but also other information that influences real-world decision making in the context of an industrial firm. Parameters representing actual time preferences, intangible costs, and marketplace heterogeneity determine technology choices in the model. This is an advantage when it comes to simulating the anticipated response of industry to a GHG tax or cap and tradable emissions program. The downside to building and maintaining a model that is technologically explicit as well as behaviorally realistic is that considerable resources are required to incorporate preferences at a detailed level. Preference estimation is a difficult endeavor and resulting parameter values are uncertain.

Implementation of a compulsory policy designed to achieve deep reductions in GHG emissions across the economy will result in feedbacks between the energy supply and energy demand sectors, as well as interactions between these components and the rest of the economy. CIMS is an integrated, energy-economy equilibrium model; however, the extent of the linkages and feedbacks incorporated into the framework is limited by the iterative process required to reach equilibrium.

We used CIMS to simulate the effect of an economy-wide GHG tax or emissions cap and tradable permits system on the Canadian industrial sector. The observed potential for changes in energy consumption and GHG emissions increased over time, reflecting additional opportunities for technological transformation afforded by capital stock turnover. This phenomenon suggests that policy-makers should consider implementing GHG policies that impose a constraint or financial penalty that is modest at first but that increases gradually in stringency over time according to a schedule announced up-front. This formulation would avoid the high costs associated with prematurely forcing the retirement of existing capital stocks, while at the same time providing a strong signal for the adoption of low-GHG technologies when capital stock is retired and new technology acquisitions occur.

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References


