ASSESSING GREENHOUSE GAS REDUCTIONS IN THE TRANSITION ECONOMIES USING A HYBRID ENERGY-ECONOMY MODEL

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ABSTRACT

In this research, the CIMS hybrid energy-economy modelling framework is used to explore the potential for greenhouse gas reductions in the Former Soviet Union and non-OECD Eastern Europe. This model is technologically detailed, behaviourally realistic and incorporates macroeconomic feedbacks, providing novel results that increase the understanding of the effects of global greenhouse gas mitigation policy. The reference case scenario forecasts emissions rising from 2.6 $GtCO_2e$ in 2005 to 4.2 $GtCO_2e$ by 2050, while energy consumption increases by 75%. The model forecasts that a GHG price starting in 2011 and rising linearly to 300 $\$/tCO_2e$ by 2050 will achieve a 50% reduction in emissions by 2050 relative to the year 2000. Carbon capture and storage and fuel switching to electricity are significant mitigation actions. Sensitivity analysis reveals that this result is robust to moderate changes in the assumed rate of industrial growth and cost of carbon capture and storage.

Keywords: Energy-economy models; Hybrid models; Climate change policy; Energy policy

Subject Terms: Energy policy – Mathematical models; Climatic changes – Government policy; Climatic changes – Economic aspects; Environmental policy – Economic aspects

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IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse gases
OECD	Organization of Economic Cooperation and Development
TE	The transition economies, nations in Eastern Europe and the Former Soviet Union. See Appendix A
FSU	Former Soviet Union
BAU	Business as usual, the model output in the absence of policy intervention
tCO_2e	metric tonnes of carbon dioxide equivalent greenhouse gasses
MAC	Marginal abatement cost
GDP	Gross domestic product
USD	US dollars
SMP	Sustainable mobility project model
DH	District heating
EIA	Energy Information Administration
IEA	International Energy Agency
RPP	Refined petroleum products
POLES	Prospective Outlook on Long-term Energy Systems
SGM	Second Generation Model
IEO	International Energy Outlook, produced by the EIA
WEO	World Energy Outlook, produced by the IEA

MIT EPPA	The Emissions Prediction and Policy Analysis model maintained at MIT

CHAPTER 1: INTRODUCTION

Background

The Risk of Climate Change and the Need for Policy

In 2007, the Intergovernmental Panel on Climate Change (IPCC) concluded that the climate is unmistakably warming, stating with high confidence that this warming is affecting Earth's natural systems (IPCC, 2007b). This warming is very likely driven by the accumulation of greenhouse gases (GHG) in the atmosphere due to human activities. Furthermore, growing confidence exists that the effects of this warming will be damaging to human and natural systems (IPCC, 2007b), making it clear that climate change is a large risk. Without a modification of human behaviour and technology, global GHG emissions in 2050 may double relative to the year 2000 (IPCC, 2007b), further exacerbating the risk. Individual changes to technology and behaviour can reduce GHG emissions. However, a reduction of more than 50% (IPCC, 2007a) below current levels is needed to effectively mitigate the risk of climate change and only government policy can induce a large enough change to achieve this. Without these policies, global GHG emissions will continue to rise and the risk of climate change will increase (IPCC, 2007b; Sokolov et al., 2008).

Not all policies will be equally effective in reducing emissions, nor will they be politically acceptable or economically efficient. Because GHG emissions are a consequence of energy consumption and land use for economic activity, they are coupled with human well being. Basic needs and the desire to improve one's quality of life are central challenges to the effectiveness climate policies. Consequently, only policies that include significant financial disincentives will achieve major reductions in GHG emissions, while voluntary measures and information campaigns will continue to fail in the face of these challenges (Jaccard et al., 2004; OECD, 2003). On the other hand, if compulsory policies are inflexible and prohibitively expensive, garnering political support is challenging. Developing nations will not participate if these policies can seriously hamper their economic progress, while wealthier nations may also reject agreements if they believe the policies threaten their existing standard of living. For a policy to succeed in reducing GHG emissions, it must be well crafted and thoroughly analysed, striking the right balance of effectiveness, cost, and acceptability.

Policy Analysis Using Models

Dozens of policies have been proposed to reduce global GHG emissions (Bodansky, 2004). Complex relationships between human behaviour, technology, and market feedbacks determine the strengths and weaknesses of each policy. An energy-economy model is a representation of these relationships that allows prior testing of a policy, providing a methodology to evaluate how a policy may reduce GHG emissions and how much that reduction may cost. Such models can improve our understanding of the each policy, helping decision makers to make better decisions.

To produce useful results, the model's representation of the economy must be appropriate. The ideal model for climate policy analysis should be technologically explicit, behaviourally realistic, and macro economically realistic (Hourcade et al., 2006). Because climate change is a global problem, the ideal model would also operate at a global level.

A technologically explicit model is able to represent the technological change induced by the pressures of climate policy. The representation of technological change is significant to forecasts of both the rate and cost of GHG abatement (Loschel, 2002).

Behavioural realism is necessary for assessing which technologies consumers and firms will adopt. Accurate portrayal of the preferences and perceptions that people have towards various technologies allows these technologies to be given realistic costs beyond purely financial costs. For example, forcing people to use technologies that they feel are more risky due to high upfront costs, or that are less familiar or less preferred imposes a cost. While consumers and firms may only perceive this cost, it is still an important element in decisions to invest in a particular technology.

The model should also include macro-economic feedbacks to accurately depict how changes in the supply, demand, and cost of goods and energy will affect the energy-economy system. This attribute affects both technological change and behavioural change, in terms of the type and quantity of fuels and energy services that are demanded. If energy costs rise due to tight demand or climate policy, consumers and firms will respond by reducing their demand for goods and services that use energy, or by switching to a cheaper source of energy. The feedbacks that determine how demand for energy services changes are fundamental to energy-economic modelling. Technological change and behavioural realism exist in this larger framework and large models should include the macro-economy to capture the economic feedbacks that will increase or reduce the ability of a policy to reduce GHG emissions.

Finally, climate change is a global risk with global causes and a wide variety of possible solutions. Furthermore, both the effect of GHG emissions and the policies that aim to reduce these emissions act over several decades. To be effective, an energy-economy model should be capable of analysing of a wide range of policies covering the major geographic areas that emit GHGs. These policies can range from technology and sector specific regulations to economy wide policies such as market-based emissions pricing (Jaccard, 2005). They must be modelled over several decades because the emissions from this system come from technologies that may remain in use for decades. Once these technologies have been acquired, they continue to affect GHG emissions over the course of their life. Without incurring significant costs, the pace of GHG abatement matches the slow rate of technology retirement and renewal. Therefore, an energy-economy model should capture the inertia and path dependency of the energy-economy system.

Energy Economy Models

Creating an accurate representation of the complex energy-economy system is challenging. In order to model it, modellers make many simplifying assumptions in their representation of reality (Fischer and Morgenstern, 2006; IPCC, 2007a). Simplifications include how geographical regions are grouped together, sectors of the economy are represented, technological detail is included, technology changes, capital is tracked within the model, how consumers and firms make their decisions, and how international trade affects the production of goods and energy.

In the past, energy-economy models have generally taken two diverging methodologies with respect to their representation of reality: the top-down and bottom-up approaches (Bohringer, 1998). Top-down models are aggregate models of the relationships in the energy-economy system, while bottom up models focus on the technological detail within that system. The differences in the assumption within these classes of models have produced differing conclusions about the cost and potential for reducing GHG emissions. This is in part because the users of these model types define the costs differently, broadening the definition to include lost value above the financial cost of a given action or restricting the definition to the net present value of financial costs associated with that action (Jaccard et al., 2003). The former definition of cost is often used in top-down modelling while the latter is often used in bottom-up modelling.

Top-Down and Bottom-Up Modelling

Conventional top-down models represent the economy through aggregate production functions for each major energy service such as electricity production or transportation. The production functions describe how goods and services are created by combining factors of production such as capital, labour, and energy. Elasticities govern the possible substitutions among these factors. For example, an elasticity determines the extent to which capital can be substituted for energy, such as in the purchase of a more efficient hybrid vehicle rather than an internal combustion vehicle. This substitution could also be for a more expensive fuel that emits less GHG per unit energy, such as natural gas instead of coal. Thus, the elasticity dictates how emissions can be reduced in the model, and what the cost of the reduction is. The elasticities are derived from historic data, are therefore inherently behaviourally realistic, and incorporate the broader definition of cost, but only to the extent that past behaviour is predictive of future behaviour. Because the relationships modelled within top-down models are large-scale processes, a subset of top-down models are capable of appropriately representing macro-economic feedbacks.

However, because production functions are aggregate representations of technology, conventional top-down models have difficulty modelling the process of technological change. Furthermore, since their behavioural realism is based on historical data, they cannot model how human behaviour may change in response to novel policies. Consequently, the energy economic system appears inflexible and top-models often forecast high economic costs to reduce GHG emissions.

Alternatively, conventional bottom-up models represent the economy through a detailed description of the technologies that provide energy services. The emissions are the result of the quantities and types of energy service that the economy demands and the technologies that meet this demand. While these models have the potential to model the dynamics of technological change, they often miss other determinants of how policies change GHG emissions. Costs are often defined as the net present financial cost, ignoring other perceived costs. Furthermore, humans are typically represented as optimizers of this cost. This simplification of behaviour ignores variations in perceptions regarding the risk of a technology, preferences, aversions to upfront investments, or the quality of service that the technology provides (Jaccard, 2005; Jaffe et al., 1999). The capacity of the economy to change in response to policy appears high as the model indicates consumers could readily switch to emerging low emissions technologies, so long as the cost over the entire lifetime of the technology is the lowest. Consequently, conventional bottom-up models may forecast lower costs and increased potential to reduce emissions

Hybrid Modelling

Policy makers have been confused when confronted by the contradictory cost estimates for reducing GHG emissions, making it difficult to develop effective policy (Jaccard et al., 2003). To bridge this methodological gap, energy modellers have developed hybrid models that use elements of both top-down and bottom-up modelling. By approaching the three elements of the ‘ideal’ energy-economy model (technological explicitness, behavioural realism, and macro economic realism), hybrid modelling attempts to provide a more useful analysis of the policy options. To this end, three general hybrid methodologies exist.

First, by coupling an existing top-down and bottom-up model, each model can inform the other iteratively over the model-run (Roques and Sassi, 2007; Schafer and Jacoby, 2006). Thus, the top-down model can provide the macro-economic conditions in which the bottom-up modelling occurs, while the bottom-up model provides a realistic forecast of technological change. Examples of this methodology include the WEM-ECO model, which couples the technology rich World Energy Model with the IMACLIM-R top-down model (IEA; Roques and Sassi, 2007), and the MARKAL model linked with the top-down EPPA model (Schafer and Jacoby, 2006) .

Second, a top-down model can incorporate an intermediate level of technological detail using modified production functions (Bohringer and Loschel, 2006; Kohler et al., 2006; Schumacher and Sands, 2007). Rather than have one function represent electricity production, the model could use a series of nested production functions, each based on a specific technology such as wind turbines or coal power. Elasticities of substitution between the various functions determine the extent to which each technology contributes to production. An examples of this second method is the Second Generation Model (Sands, 2004; Schumacher and Sands, 2007).

Third, a bottom-up model can include a reduced representation of the macro-economy, such as energy price and demand feedbacks, elasticities that govern changes in energy service demand, and equilibrium of energy supply and demand. The POLES model can be classified under this method (Criqui et al., 1999), as can CIMS, the modelling framework used in this study (Bataille et al., 2006).

CIMS-Global

Overview

The CIMS modelling framework is technologically explicit, behaviourally realistic, and includes a representation of the macro-economy over a 50-year period. The following section describes the unique nature of the CIMS model structure and its ability to provide novel results for the analysis of GHG mitigation policy. Until the present CIMS has not had global coverage. This project is part of a the larger CIMS-Global effort that will extend CIMS beyond its current application to Canada, China, and the US.

Four regions are being modelled using CIMS: (1) the rest of the developed nations (OECD); (2) transition economies in Eastern Europe and the former Soviet Union; (3) Asia, excluding China; and (4) developing countries in Africa, the Middle East and Latin America.

The regional aggregation is based on the aggregation in the Global MARKAL-Macro model where model regions are grouped together based on economic and developmental similarity rather than geographical proximity (Barreto and Kypreos, 2006). The CIMS-Global aggregation makes policy modelling possible without the additional work needed to produce more disaggregated regions. This approach is viable especially to the extent that each of the large regions in CIMS-Global are likely to adopt similar policies. For example, the OECD countries may adopt compulsory schedules to cap their GHG emissions, while the developing nations may participate with less stringent policies that would support their economic development. Furthermore, this regional aggregation also facilitates using data from the International Energy Agency (IEA) since it uses similar geographical groupings for their energy statistics.

This document focuses on the modelling of the second region, the transition economies (TE). This region includes all nations of the former Soviet Union (FSU) and the European nations that are not members of the OECD. I will refer to this region as the "study region" and the model as CIMS-TE. Appendix A lists the countries included in the study region.

Justification for CIMS Global

Table 1 compares existing global energy-economy models and CIMS-Global against the three attributes of the ideal model and the modelling methodology used: simulation, optimization, or computable general equilibrium (CGE). Although optimization and simulation models use a bottom-up methodology and CGE models use a top-down methodology, most current models are moving towards a hybrid-modelling framework using one of the general methods described earlier[1]. The two models that are most similar to CIMS are POLES and MARKAL SAGE. POLES is a partial-equilibrium simulation model, however it does not have the same level of technological detail as CIMS does, nor does it include behavioural realism based on empirical study. MARKAL SAGE does have a high level of technological detail; however, it uses optimization rather than simulation to produce its results.

Table 1: Comparison of global energy-economy models

	Type	Technological Detail	Behavioural Realism	Macroeconomic Feedback	Reference
Global Multiregional MARKAL (GMM)	Optimization	All sectors	Not addressed	Partial	(Barreto and Kypreos, 2006)
MESSAGE-MACRO	Optimization	All sectors	Not addressed	Partial	(International Institute for Applied System Analysis)
POLES	Simulation	All sectors, low detail	Not addressed	Partial	(Criqui et al., 1999; EC, 2006)
MARKAL SAGE	Optimization	All sectors	limited	Partial	(EIA)
AMIGA	CGE	Supply only	Implicit	Full	(Mintzer et al.)
GTAP-E	CGE	Supply only	Implicit	Full	(Burniaux and Truong, 2002; Dagoumas, Papagiannis, and Dokopoulos, 2006)
MERGE	CGE	Supply only	Implicit	Full	(Manne and Richels)
MIT-EPPA	CGE	Supply only	Implicit	Full	(Paltsev et al.)
SGM	CGE	Supply only	Implicit	Full	(Sands, 2004)
WEM-ECO	CGE	All sectors, low detail	Implicit	Full	(IEA; Roques and Sassi, 2007)
CIMS-Global	Simulation	All sectors, high detail	Yes, based on empirical study	Partial	

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[1] Optimization and simulation are bottom-up type models. Optimization models solve to minimize the cost of the energy system subject to constraints, and simulation models solve recursively, with the results of one time-step depending on the previous results. CGE is a type of top-down model in which supply and demand are balanced for all goods and services (full-equilibrium). Partial-equilibrium means that only supply and demand for energy is balanced, or that only supply or only demand are analyzed.

The way CIMS models the energy-economy system is unique. CIMS-Global will provide novel results that can be used in comparative studies with other models for the analysis of global GHG mitigation policy. From these comparisons, we can gain new insights into the global energy-economy system and the policies that will effectively reduce GHG emissions. With over 2500 technologies, CIMS provides more technological and process detail across all energy intensive sectors of the economy than other global hybrid models. Results are derived using behavioural parameters based on empirical study, thus the level of behavioural realism is also greater than in other models (Axsen, 2006; Nyboer, 1997). The macro module is well developed providing macro-economic realism through price feedbacks to energy consumption and economic activity. Finally, the results come from a simulation framework where the output of each model time-step depends on the path taken in earlier time-steps rather than from cost-optimization with perfect foresight. Therefore a simulation model shows what effect policies may have given the realities of firm and household decision-making processes instead of an idealized path to lower emissions, capturing the path-dependant nature of the energy-economy system (Jaccard et al., 2003).

Research Objectives

The research objectives of this paper are as follows:

1. Develop a CIMS model that can forecast a plausible "Business as Usual" (BAU) scenario for the TE. This BAU scenario must forecast the energy use and emissions in the TE to 2050 in the absence of GHG reduction policies. The forecast should be studied in the context of other forecasts for the TE in order to support or challenge the existing modelling results for the region.
2. Determine the GHG emissions price-path that results in a 50% regional reduction of GHG emissions from the year 2000 by 2050 and compare that to the path that would achieve a 50% global reduction from the same baseline while allocating per capita GHG emissions equally across the world.

3. Study the methods of abatement to understand how GHG emissions in the TE may be reduced, for example by a change in fuels or a change in energy efficiency, and from what sectors these reductions may come.
4. Examine and compare the cost of emissions reduction in the TE with other studies of the region and with other CIMS regions to understand how different modelling methodologies affect abatement cost and to determine where there is the greatest potential for low-cost GHG abatement.
5. Explore the uncertainty in the model results by determining the sensitivity of the GHG reductions to two key parameters, the rate of industrial growth in the TE and the cost of carbon capture and storage (CCS).

Report Outline

Energy-economy models help assess GHG reduction policies before they are enacted. Chapter 1 has explained that while these models have used diverging methodologies, the 'ideal' model for this task should be technologically explicit, behaviourally realistic, macro-economically realistic, and capable of modelling a variety of policies at a global level over several decades. The purpose of this project is to extend the coverage of the CIMS model to the Transition Economies (TE), helping to build the CIMS-Global model that better approximates this 'ideal' model.

Chapter 2 describes the CIMS modelling sequence, as well as the methodology for building the model, analyzing policy, and studying uncertainty in the model outputs. Chapter 3 goes into detail on the various economic sectors of CIMS-TE, highlighting important data sources, assumptions, and the modifications to the sector models that were necessary to accurately represent the study area. Additionally, chapters 2 and 3 document the construction of CIMS-TE to facilitate future refinements of the CIMS-Global project.

Chapter 4 presents the results of the BAU simulation and the policy simulation, while describing from which sectors and by which methods CIMS-TE anticipates emissions reductions. This chapter also includes the results of the sensitivity analysis on the rate of industrial growth and the cost of CCS in the study area.

In Chapter 5, I compare the BAU forecast to the results for the study area produced by other models, assessing whether the CIMS-TE BAU is consistent with several other reference case forecasts. I then examine the cost of reducing GHG by comparing trends in the marginal abatement costs from several CIMS regions and to other models of the study area. I finish chapter five by discussing the strengths and weakness of this model's application to the TE, and how future work can improve CIMS-TE. Chapter 6 summarizes the key findings and conclusions of this project.

CHAPTER 2: METHODOLOGY

The previous chapter presented the need for a global CIMS model for the analysis of international GHG reduction policies. This chapter explains the CIMS modelling framework, demonstrating how it incorporates the three attributes of the ideal energy-economy model. I then elaborate on the process and challenges of building a new CIMS model for the transition economies (TE), explaining how I calibrated it to historic data and used it to make a business as usual (BAU) forecast. I also explain my methodology for developing a policy forecast and my methodology for analysing this forecast and studying the uncertainty using a limited sensitivity analysis.

CIMS modelling approach

The CIMS modelling approach pursues the three attributes of the 'ideal' energy economy model. Explicit processes and technologies that change over time, supply the energy services that are demanded by the sector output forecasts. Three behavioural parameters ensure that firms and households acquire technologies according to an accurate representation of decision-making. Finally, macro-economic feedbacks iteratively adjust the sector and process outputs according to how a policy changes the cost of energy services or the cost of production in a given sector.

Over each five-year time step, CIMS describes the output in the model sectors as amounts of energy services demanded. It then simulates the processes and technologies that meet this demand. The sector outputs are set using externally supplied forecasts, such as the quantity of metal produced, or the quantity of person kilometres travelled, for each time step from the present to 2050. Each output is subdivided into a variety of processes. For example, several processes supply 'tonnes of metal', such as steel or aluminium manufacture, while urban or intercity travel supplies person kilometres travelled. Within the processes, technologies, such as different steel furnaces or different modes of urban travel, supply the corresponding energy service. In each time step, the demand for each energy service is calculated. Technology that is already in use within the model, known as the stock, meets some of that demand. However, because demand for energy services may grow and old technologies are retired, there will be a difference between the amount of energy services that the firms and consumers demand and the amount the stock can provide. New technologies are acquired to close the gap between supply and demand and it is through this retirement and acquisition of stock that the technological stock within CIMS evolves. Technological change from stock turnover can decrease the quantity of GHG emissions per unit of energy services provided. If a GHG mitigation policy is guiding this evolution, the rate of this decrease will be greater than in the BAU.

CIMS simulates how processes and technologies are chosen using an algorithm that accounts for the financial cost as well as behavioural elements of decisions making, thus including behavioural realism. Three empirically based parameters represent behaviour: the discount rate, the intangible cost, and the heterogeneity of markets. These parameters may be different for each technology. The first parameter, discount rate, is a measure of how consumers value current costs and benefits compared to future costs and benefits. The second parameter, the intangible cost, represents all non-financial costs of a technology, including the influence of consumer intangible preferences and perceptions of risk. For example, the inconvenience of riding public transit incurs a cost over using a personal vehicle, as would the perceived risk of using an experimental hydrogen-fuelled furnace rather than a standard natural-gas furnace. The third parameter, market heterogeneity, represents the relative importance of perceived and real costs in the technology choices of firms and households. On one extreme, these costs have little influence over market shares. At the other extreme, costs are the only factor contributing to technology choice and all consumers are assumed to make same choice, as would be portrayed by an optimization model.

Macro-economic realism is included by balancing energy and energy service supply and demand through iterative simulations in each time step. Energy service elasticities of demand adjust the output of each sector based on changing production costs. These elasticities determine the magnitude of change in energy service demand based on the magnitude in change of the cost of production. In CIMS, the cost of production may change under the effects of policies or different energy prices, an effect that is most noticeable in sectors with high energy and emissions intensities. The market share algorithm ensures that an adequate stock of technologies meets the demand for each energy service.

After balancing supply and demand of energy services, CIMS does the same for energy consumption. The simulation ensures that the amount of each energy type consumed is the same as the amount the energy supply sectors produce. For example, if more electricity is used than is produced, CIMS iterate once more, adding more electrical generation capacity. However, this new capacity will change the price of electricity, which may changes the demand again. The iterations continue until the change in demand falls below a 5% threshold.

Business as Usual Model Development

The CIMS modelling sequence determines the BAU forecast of the energy consumption and emissions to 2050. A plausible forecast depends not only on the model structure, but also on the data contained in the structure. To meet my first research objective and produce a plausible BAU forecast for the TE, I had to modify the data inputs and structure of CIMS so that it would better represent the study area.

Challenges

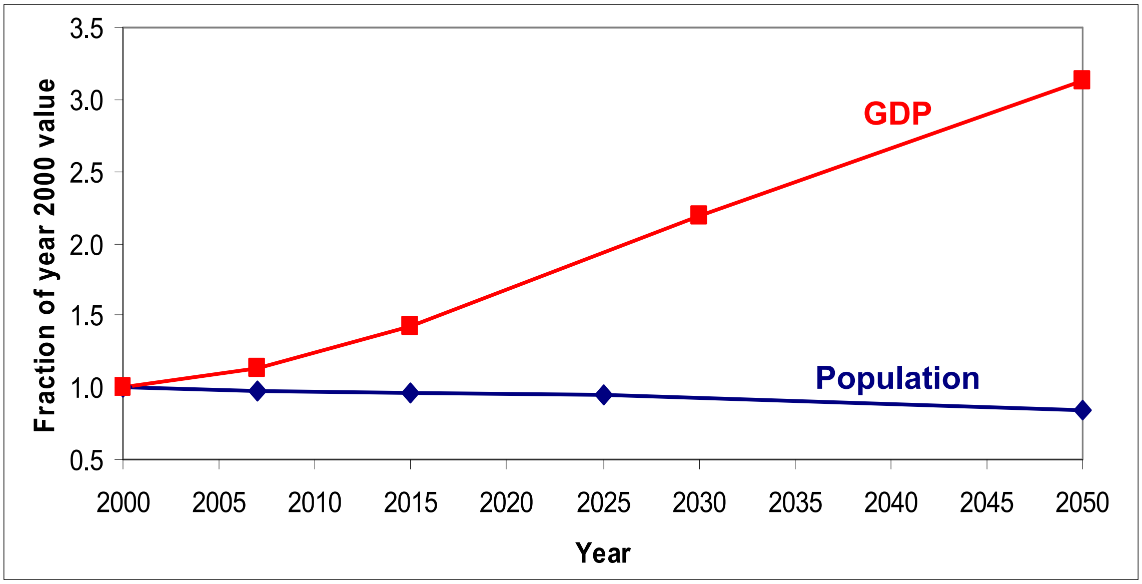
Applying CIMS to the TE required a large amount of technological, behavioural, and macro-economic data, as well as forecasts of this data into the future. Unfortunately, some of this information was either unavailable or non-existent. The original methodology for this project involved finding another global model that was technologically explicit and using its database to populate the CIMS-Global models. However, very few suitable databases existed and those that did exist were not available for this research. To move forward with model construction, I had to develop a knowledge base of the study area to guide the assumptions that filled the data gaps.

The data that were available were rarely in a form that I could use directly in CIMS. Essentially, I was trying to complete a puzzle with too few pieces coming from many different sources. One of the most common challenges was that the available data were for a regional aggregation other than the TE. For example, where data did not exist for the TE, they were often available for Russia, the Commonwealth of Independent States, the former Soviet Union, or Eurasia. Where data inputs to CIMS-TE were absolute quantities, sector outputs for example, I scaled available literature values based on a comparison of the population or energy consumption in the TE with the region from which the data were collected. Where appropriate, I assumed that data for one part on my region were representative of the whole region. This could be for energy prices, technology types (e.g. natural gas vs. oil home furnaces), and fuel efficiencies. Fortunately, the non-TE regional aggregations are reasonable approximations of the TE. Russia consumes half of all energy in the TE, while the former Soviet Union consumes close to 90% of the energy in the TE (IEA Statistics, 2003a), justifying the application of data from these regions to the entire study area.

General Trends in the Transition Economies

I used several guiding assumptions about demographic, economic, and technological trends during the development of the CIMS-TE BAU forecast. In general, the TE population is expected to decline slightly, while GDP is expected to rise by 2050 (Figure 1). Because the population is effectively steady, per capita GDP will be increasing at roughly the same rate as GDP. I used this trend to indicate rising personal affluence, guiding my assumption of rising sector outputs despite the declining population. The CIMS-TE average GDP growth is 3.9% per year, based on the rate used by the POLES model (EC, 2006); thus GDP is larger by a factor of three in real terms in 2050. Other rates are possible and the POLES value is more conservative than other forecasts, like the Energy Information Administration (EIA) rate of 4.4% to 2030 (EIA, 2007b)

Figure 1: Population and GDP forecasts for the TE relative to the year 2000



Source (EC, 2006; United Nations Population Division, 2007)

Due to the Communist legacy, the nations of the TE have very high energy intensity and most of the capital stock is not energy efficient (IEA, 2006a; IEA, 2007). In 1999, the energy intensities (energy/GDP) of the TE countries ranged from 1.2 to 10 times higher than the US value. The Russian value was over four times higher than the US value (Cornillie and Fankhauser, 2004). Therefore, in building the model, I assumed the technology stock was of the lowest efficiency available in CIMS unless data indicated otherwise.

Another important consideration is the development of the economic system in the TE. Consistent with the forecasts of the major energy agencies, I assumed the TE region would continue the transition towards liberalized free-market economies and consequently final energy prices will rise as subsidies are phased out (EIA, 2007a; IEA, 2002). Additionally, consumers and firms, rather than a central authority, select which technologies to use, as modelled by the market share algorithm.

In all other domains of model construction, I assumed the parameters for CIMS-TE are the same as the parameters in the Ontario model from CIMS Canada, unless I had a data source that indicated changes were necessary. This means that most of the behavioural parameters, the sector output elasticities, the types of processes used within the sectors, and the technology parameters other than stock, are unchanged. In chapter 3, I describe the significant changes at the sector level.

Model Construction

While building the model, I prioritized any data searches and changes to the model structure based on their impact on the model's results. I allocated more time to the sectors in CIMS-TE that are large energy consumers or large GHG emitters. For example, residential GHG emissions in the TE are 30 times larger than coal mining emissions; therefore, I gave more attention to the residential model to improve its accuracy. As well, I more thoroughly researched large-scale opportunities for GHG mitigation, such as the physical and political limits on the development of hydroelectric power and nuclear power, again because these considerations have significant effects on both the BAU and policy emissions forecasts. Under this framework, the development of the BAU forecast for CIMS-TE followed three major steps.

Model selection

The first step was to select an existing CIMS model whose structure best matched the new study area and then adust the model structure wherever it was not consistent with the study area. For example, Russian oil resources are becoming heavier and sourer; therefore, I based the petroleum-refining sector on a Canadian refinery model that processes a similar grade of oil. However, I had to change the ratio of crude oil to output because the final product mix of these two regions is different. Generally, starting with the most applicable Canadian sector model reduced the workload necessary to build the model and it ensured that wherever data for the TE were not available, the default values in CIMS would be most appropriate for the study area.

Base-year outputs, forecasted outputs, and technology stocks

The second step was to locate quantity, or output, data for the year 2000 for each sector, process, and technology. These data came in varying degrees of detail from several sector specific sources. Finding forecasts of sector output proved to be more difficult than finding the base year outputs. In some cases, especially the energy supply and residential sectors, forecasts were available until 2020. However, few forecasts extended beyond 2010. Wherever there was no forecast I used the GDP forecasts from the POLES model (EC, 2006) to approximate the changes in sector output. Finding forecasts for process changes or base year technologies within the sectors was even more difficult. In most cases, I left these identical to the Canadian model, subject to my assumption of low energy efficiency.

Energy price forecasts

The third step was to input energy price forecasts into CIMS-TE. I derived base-year energy prices from IEA historical data ranging from 2000 to 2007. However, not all countries in the TE report their data and those that did report did not do so every year. Therefore, it was not possible to simply input weighted average energy prices for CIMS-TE. While establishing energy prices for the years 2000 to 2005, I used assumptions where data were lacking and created a composite price for my entire model region based on the prices of the largest nations in the IEA data. In general, Russian energy prices were half the corresponding price in other countries and Russia consumes roughly half of any given fuel in the TE. Therefore, the composite base year-prices are 50% higher than the Russian prices to account for regional variation in the TE.

No forecasts of energy prices in the TE to 2050 exist, so the values in the model reflect regional conditions and global expectation for the long-run price of oil. Energy prices in the TE are below market value, especially in Russia, due to government subsidies and price fixing. However, across the region, many price reforms are either underway or planned (EIA, 2007a; IEA, 2002). I considered these reforms when making the price forecasts to 2015, assuming fuels would approach their market value by this date.

For the long-term energy price forecasts, I applied the same trend to the price as exists in CIMS Canada, based on a long-run oil price of 64 2005USD/barrel. Regional differences between Canada and the TE will surely result in different energy prices, but there are enough similarities to justify applying the same trend in energy prices to both regions while there is a lack of a better forecast. Both regions participate in the global oil market and both are expected to be important exporters of fossil fuels, so it is possible that the relative price of energy in both regions could follow the same trajectory.

Calibration

After building the model, I calibrated it to historical data for the year 2005, ensuring that the simulation starts from the correct reference. I adjusted CIMS-TE so its outputs of energy consumption by sector, energy consumption by fuel, and energy exports or imports matched data from the IEA 2005 energy balances for the former Soviet Union and non-OECD Europe. These energy balances provided a detailed account of how the TE produced and consumed energy, enabling me to match total energy consumption and energy trade to within 5% of the historical data while achieving a reasonable fit for consumption by fuel, consumption by sector, and hence GHG emissions by sector. Calibration also allowed me to compare CIMS-TE's forecasts with historical trends, so I could ensure that, at minimum, the model was not forecasting wildly divergent future trends in the first five to ten years of the simulation.

While calibration does not guarantee that the model will accurately forecast the future, it is equally important to model construction because it ensures the internal consistency of the model. The model is built on a multitude of assumptions from many data sources. Calibrating to a single high quality data source at the sector level gives a degree of confidence that these assumptions are consistent with reality and do not contradict one another. In the instances where the model needed adjustment, I altered assumptions to fit the calibration data rather than changing elements founded on other data sources. In some cases, I knew what the sector output was, particularly for the energy supply sectors, while in other cases, such as transportation, I had data covering the efficiency of energy use in the sector. For the former case, I calibrated by adjusting the energy intensity of the sector, while in the latter I adjusted the sector output. Any other errors or inconsistencies from historical data became apparent and were corrected during calibration.

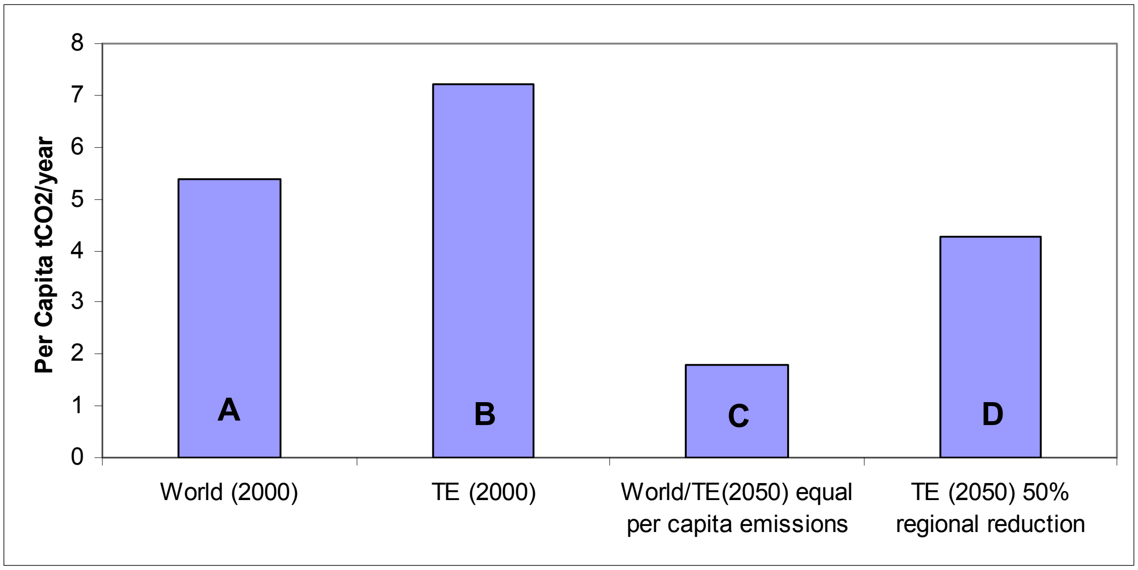
I used calibration sectors that matched the sector aggregation in the IEA energy balances, subdivided as electricity, residential, commercial, transportation, industry, and energy supply. Appendix B contains detailed calibration results and documentation disaggregated by sector.

Policy Simulation and Analysis

IPCC Stabilization Targets

Global atmospheric CO_2e concentration should be stabilized at 450 ppm by 2050 to reduce the probability of warming by more than 2.5°C (IPCC, 2007a). Although, this is the most stringent stabilization goal presented by the IPCC, it substantially reduces the risks created by climate change (IPCC, 2007a) and I have chosen it as the global target for this study. This target requires global emissions in 2050 to be 50% less than they were in the year 2000. Annual global emissions in 2000 were 44 $GtCO_2e$ (IPCC, 2007b). Of this amount, 75% is modelled by CIMS. The rest is due to land use, thus global emissions in CIMS would be 33 $GtCO_2e$, equivalent to an average of 5.4 tCO_2e/person each year (Figure 2, **A**). Global emissions as modelled by CIMS would have to fall to 16 $GtCO_2e$ per year in 2050 to reach the 50% goal.

Figure 2: Per capita CO_2 emissions targets in 2000 and 2050



Emissions in figure are those modelled in CIMS. Includes combustion and fugitive emissions, but not waste or land use emissions. Source (IPCC, 2007a; United Nations Population Division, 2007)

The TE's share of emissions in the year 2000 was about 2.5 $GtCO_2e$, equivalent to per capita emissions of 7.2 tCO_2e/person each year (Figure 2, **B**). To achieve the stabilization goal I describe, emissions in the TE, as modelled by CIMS, would have to fall to 1.25 $GtCO_2e$ per year in 2050. This is equivalent to 4.5 tCO_2e/person per year by 2050 (Figure 2, **D**), assuming the world population increases by 50% in that time (United Nations Population Division, 2007) and the TE's population follows the trend I use in this study (Figure 2). Alternatively, if per capita emissions were to equalize globally by 2050, emissions in the TE would have to fall to 1.8 tCO_2e/person per year (Figure 2, **C**).

Fixed Regional GHG Reduction vs. Contraction and Convergence

Several policy architectures could reach the global target of 16 $GtCO_2e$ per year in 2050, but they may not all equitably distribute the burden for this achievement. So far, I have described a fixed region reduction of 50% whereby each country or region would cut its emissions by half their levels in the year 2000. This fixed regional reduction would achieve the desired environmental goal, but it may be inequitable to some. GHG emissions are currently coupled with energy use, economic development, and human well-being and to some extent, they will remain that way by mid-century. If each country agreed to reduce its emissions by an equal proportion from the same base year, this would allocate a very small proportion of annual emissions to developing countries, leaving them struggling to improve their standard of living. Additionally, the total stock of GHGs in the atmosphere, more so than the annual flow of emissions, causes climate change. Developing nations have contributed very little to this stock of GHGs, so one could argue that it would be more equitable if these nations also contributed less to reducing the flow of emissions.

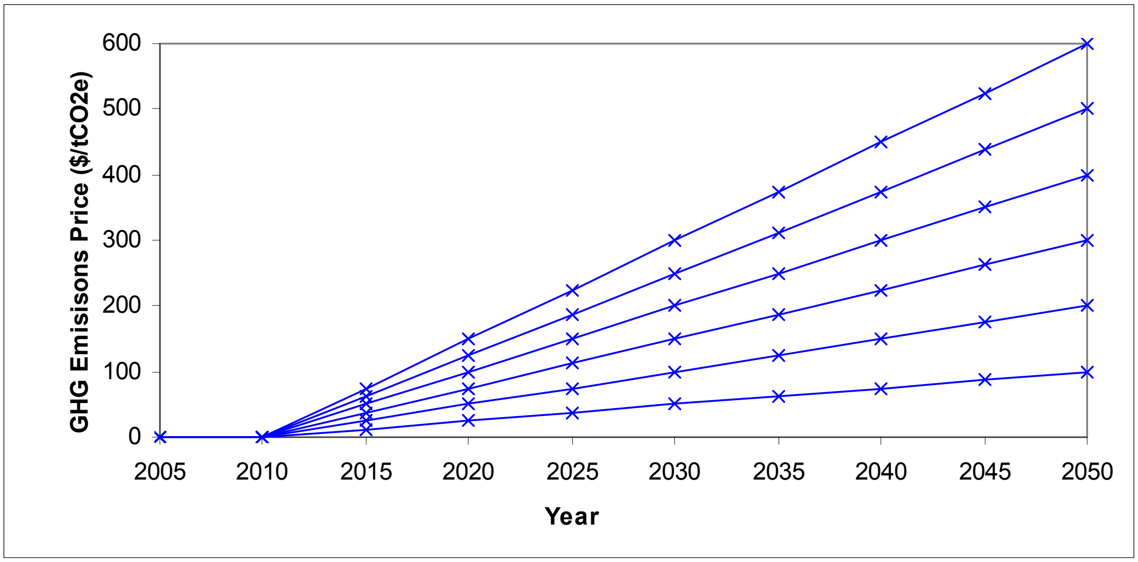
A variety of policy architectures deal with equity issues and one of the more popular among them is "contraction and convergence". This architecture, originally developed by the Global Commons Institute, requires nations to agree to a 'safe' stabilization level, which determines annual global emissions, by a set date. Nations would increase their emissions until all regions have equal per capita emissions at the given date (Bodansky, 2004).

Under both policy architectures, the per capita emissions in the TE would have to fall. However, under contraction and convergence, per capita emissions in the TE and elsewhere in the world would have to be 1.8 tCO_2e/person per year (Figure 2, **D**), similar to the target used by Böhringer and Welsch (2004) in their study of this policy architecture. This target would be a threefold reduction from the per capita emissions if the TE were pursuing a 50% cut in emissions from the year 2000. Consequently, emissions in the TE would have to fall by over 80%, a typical requirement of industrialized nations under more equitable policy architectures (den Elzen et al., 2005; Jacoby et al., 2008).

GHG Emissions Price-paths

In my analysis, I assessed the effects of an economy wide price on GHG emissions in the study area. This analysis satisfied my second research objective, to investigate which GHG price-pathways might achieve the policy goals of a fixed regional reduction in GHG emissions and a global contraction and convergence of per capita emissions. The GHG price that CIMS simulates is the same as an economy wide carbon tax, assuming the tax is applied equally to all sectors, without exemptions or flexibility mechanisms. I assume these policies begin after 2012, at the start of the post-Kyoto period. These taxes increase linearly until 2050 and I refer to them by the price they reach in 2050. I tested carbon prices that rose from 0 in 2010 to 50 \$/tCO_2e through 600 \$/tCO_2e by 2050. Figure 3 shows the trajectory of a subset of these emissions prices. The simulation of these GHG prices does not include revenue recycling and it assumes consumers and firms have average cost GHG precognition, meaning the average cost of the GHG price over the lifetime of the technologies is used in the market share algorithm.

Figure 3: Sample GHG emissions price-pathways



All prices in this study are in 2005 US dollars

None of these price-pathways is an actual policy suggestion. Rather they are an exploratory tool I used to test the magnitudes of emissions reductions possible within the TE using a price mechanism. In an effort to find an emissions price-pathway that would achieve the per capita goal for the contraction and convergence policy architecture, I tested pathways upwards to 600 \$/tCO_2e by 2050. Other studies examining deep reductions by 2050 have used GHG prices in this range. A MIT study of equity in global policies used GHG prices as high as 450 \$/tCO_2e by 2050 (Jacoby et al., 2008). Although the 600 \$/tCO_2e did not achieve the contraction and convergence goal, I did not continue to test higher carbon prices. As the GHG price rises, it is less clear if CIMS-TE is capturing the full extent of technological and behavioural changes that would accompany such a large change in prices. CIMS-TE will only show the GHG price response based on technology and behaviour permitted by the model's current technology options. Extremely high GHG prices could produce technological and behavioural changes that are outside the range of what CIMS-TE can simulate.

Wedge Diagrams and Marginal Abatement Cost Curves

I addressed my third and fourth research objectives, to explore the methods and cost of GHG abatement, using wedge diagrams and marginal abatement cost (MAC) curves. The wedge diagrams allowed me represent the relative contribution of different GHG abatement options. MAC curves represent the cost of reducing GHG emissions in the TE and allow comparison of these costs between regions and model forecasts.

GHG abatement actions can be classified under four broad categories: increasing energy efficiency, switching to fuels that emit less or no carbon per unit energy, reducing or shifting economic output, and using GHG controls such as carbon capture and storage (CCS). Wedge diagrams portray the contribution of each abatement action to reducing GHG for a given policy over the entire model run. They also display the cumulative emissions avoided, which is the area of the abatement wedges, as well as the cumulative GHG emitted.

MAC curves display the quantity of abatement, or proportion of abatement relative to a baseline, that happens at a given GHG price. Steep MAC curves indicate rapidly rising abatement costs, because the GHG price must rise significantly for each unit of GHG avoided. Conversely, a shallow MAC curve shows that more emissions can be avoided for a given GHG price, indicating slowly rising abatement costs. A short-run MAC curve will be steeper than a long-run curve because reducing GHG over a short time span requires expensive adjustments, such as the early retirement of capital stocks and the adoption of higher cost technologies. The same reductions over the long run will be less costly because the natural turnover of capital stocks allows emissions to be reduced as new equipment is needed while benefiting from economies-of-scale that can reduce the cost of new technologies.

In this study, I use MAC curves to compare the cost of abatement among the CIMS-Global regions with other estimates for the TE. A comparison of MAC curves from similar models can indicate which regions could reduce their emissions at the lowest cost. Consequently, MAC comparisons may allow better informed negotiations of international commitments to reduce GHG emissions, while indicating how cooperation and emissions trading might help achieve these commitments. Alternatively, a comparison of MAC curves from different models can indicate how model choice affects the forecasted abatement costs and, hence, how it affects policy analysis.

Uncertainty and Sensitivity Analysis

A model is an abstraction of reality and every assumption, simplification, and data source the modeller uses introduces uncertainty into the results. Uncertainty exists as either parametric or structural uncertainty, the former coming from error in individual values in the model, while the latter comes from the relationship within the model itself (Morgan and Henrion, 2006). This project is essentially a study in structural uncertainty, as it demonstrates how a new global modelling framework may produce different results from existing global models. Within this study, I have made an additional exploration of parametric uncertainty.

Parametric uncertainty exists in all parts of the model because none of the technological data, behavioural data, macro-economic data, and output forecasts are completely accurate. Again, this information came from many different sources and was often incomplete, thus, a great deal of the model is based on inferences and assumptions founded on the aggregate depiction of energy intensity in Cornillie and Fankhauser (2004), IEA (2002), and IEA (2006). Despite this reality, much of the uncertainty has only a slight effect on the regional results of CIMS-TE. While it is impossible to perfect every part of the model, it is important to identify the most uncertain parameters based on the magnitude of effect they have on the regional GHG emissions and energy consumption forecasts.

A full sensitivity analysis on every uncertain element in the model, tracking how the model outputs change as the parameters change, would be the ideal way to determine which parameters are most problematic. Unfortunately, the size and structure of CIMS-TE does not lend itself to this type of testing so I had to select by inference which parameters to explore with sensitivity analysis. One can infer that the model results may be sensitive to parameters that exist in all parts of the model, such as macro-economic relationships, ubiquitous technologies, and parameters in the market-share algorithm.

Several sensitivity analyses have been conducted with other versions of CIMS. Because behavioural parameters are difficult to measure (Jaccard, 2005) and cannot be assessed for every technology in CIMS, they have already been included in earlier analyses. Tu (2004) found that within the range he studied, changing behavioural parameters only changed energy consumption by 5%. Melton (2008) studied the effect of changing sector forecasts, the physical limit to carbon capture and storage and nuclear energy, as well as the price and quantity feedbacks in the residential and commercial sectors, finding that they all had significant impacts on the outputs. Since the model structures of all CIMS regions are very similar, these results apply to CIMS-TE as well.

In this sensitivity analysis, I examine the cost of carbon capture and storage (CCS), one of the methods that contributed most to GHG reductions in the policy simulation. In CIMS-TE, CCS uses one technology that represents the cost of capturing and storing carbon. This cost determines how much CCS operates under a given policy and is based on the cost of the necessary technology and the accessibility of the geological storage reservoirs. Because the TE is a large region with low to moderate population density, spanning many prime CO_2 storage sites (EIA, 2008; IEA, 2004b), I did not put a physical limit on CCS. While physical feasibility may not be an issue, the technology is only now approaching commercialization and the economic potential is less certain. The technology data, including cost, are based on the 2005 IPCC study of CCS, but the costs may be significantly higher than predicted (Rubin et al., 2007). Due to the pervasiveness of CCS in the model, its importance in the policy forecast and the uncertainty in its cost, I performed a sensitivity analysis on the cost of CCS. I examined the effect of a CCS cost that is up to three times higher than the base value in CIMS, consistent with initial surveys of CCS test facilities (Rubin et al., 2007). The upper range in my analysis is equivalent to a 60% percent increase in the capital cost of CCS technologies in the electrical sector and a 100% increase in the capital cost of industrial CCS applications.

I also conducted a sensitivity analyses on the rate of industrial growth. The industry sector includes the manufacturing and resource extraction sectors in CIMS-TE. It does not include the energy supply sectors (petroleum crude, coal mining, petroleum refining, and natural gas extraction) and the electricity sector, whose output forecasts are well documented and extend to 2030. These forecasts were not available for the industrial sectors, extending to 2010 at best. Consequently, I had to make basic assumptions about how they would grow to 2050.

I linked industrial output directly to GDP growth, allowing no structural change within the economy in the BAU forecast. Consequently, the industrial sector is one of the most significant energy consumers and GHG emitters in the BAU and policy forecasts. However, it is possible that more economic growth would occur in the non-energy intensive sectors of the economy such as the service or knowledge sectors. Other models of the region use varying assumptions about economic growth and how industry will grow in relation to the economy (see EC, 2006; EIA, 2007b). Because of the significance of the industrial sector to the model results and the possibility of an economy that grows differently than I assumed, I examined the effect of changing the ratio of the GDP growth rate to the industrial growth rate from 1:1 through to 1:0.25. This latter ratio, which assumes the economy grows four times faster than industrial output, makes the increase of industrial energy consumption consistent with the value produced by the POLES model (EC, 2006).

CHAPTER 3: ENERGY SECTOR STRUCTURES AND ASSUMPTIONS

The previous chapter described the CIMS modelling sequence, as well as the methodology for building the model, analyzing policy, and studying the uncertainty of the model outputs. This chapter goes into detail on the various energy sectors of CIMS-TE, highlighting important data sources, assumptions, and modifications. I aim to provide enough information to familiarize the reader with the content of CIMS-TE, while giving credibility to the model and allowing others to challenge the larger assumptions contained therein. Additionally, CIMS-TE will inevitably be modified and refined. This endeavour will rely on the documentation contained in this chapter to work toward a more internally consistent and accurate future version of the model.

Sector Aggregation, Emissions, and Energy Consumption

For this study, I organized the 16 CIMS-TE sector models under five larger energy sectors (Table 2)[2].

Table 2: Sector aggregation

Energy Sector	CIMS-TE Sectors
Transportation	Personal Transportation, Freight Transportation
Residential and Commercial	Residential and Commercial
Electricity	Electricity
Industry	Iron and steel, metal smelting, pulp and paper, chemical products, industrial minerals, mining, other manufacturing
Energy Supply	Petroleum crude, natural gas, petroleum refining, coal mining

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[2] Refer to Appendix C for details on the data sources for each sector. Appendix D contains the reference case output forecasts for each of the disaggregated sectors listed in Table 2.

Table 3 displays historical emissions and energy consumption globally and in the TE, to showing their importance relative to one another and within the global energy system. The study area accounts for roughly 8% of global emissions and 8% of global energy consumption.

Table 3: Sector emissions and energy consumption, 2005

Energy Sector	Emissions[a] ($GtCO_2e$)	Total Energy Consumption[b] (EJ)
Transportation	0.39	4.4
Residential and Commercial	0.53	11.0
Electricity	0.54	14.2
Industry	0.70	10.4
Energy Supply	0.50	4.8
TE Total	**2.66**	**44.9**
World Total	33.00	507

[a] Emissions included in CIMS, not including land use changes

[b] Includes primary and secondary energy consumption, but not petroleum feedstock

Source: (IEA Statistics, 2003a; IPCC, 2007b)

Transportation

The Transportation sector accounted for 15% of emissions and 10% of final energy consumption in 2005, consuming mostly refined petroleum products (RPP). The Sustainable Mobility Project (SMP) model, maintained by the IEA, is the data source for the CIMS-TE sector. The SMP model provides detailed historical data and forecasts on modes of personal and freight transportation, fuel efficiencies, fuels consumption, and passengers per vehicle. Despite this wealth of data, the CIMS-TE transportation sector includes several assumptions that allow it to represent the actual transportation sector in the TE. After the initial construction of the sector, it consumed double the energy reported in the SMP model even though the transportation demand is from the SMP model. Correcting this issue required reducing the energy intensity of both the freight and personal Transportation models from the original values used in CIMS Canada.

To reduce energy consumption in the freight sector, rail freight had to be more competitive relative to truck freight, requiring a lower intangible cost than in the Canadian model. My assumption is that the rail freight network is more extensive in the TE and therefore more attractive to consumers, allowing it to maintain a larger market share relative to freight trucks than it would in Canada. I also reduced the intangible costs associated with electric freight trains to ensure that the sector consumed a quantity of electricity consistent with historical data. Based on the electricity consumption within the TE, electric rail freight is already prevalent in the study region. Therefore, it would carry a smaller perceived risk and would be more competitive relative to other rail technologies.

In the personal transportation sector, I adjusted the energy efficiency of personal and transit vehicles. Contrary to the low energy efficiency in the rest of the study area, the personal vehicle fleet in the TE is more energy efficient than the Canadian fleet, possibly due to smaller vehicle sizes and smaller engines. I had to reduce the average fuel consumption of cars and trucks in CIMS by almost 20% to match the sector output and energy consumption with historical data. Transit vehicles in the TE have an average 50% more passengers than do Canadian vehicles (IEA/WBCSD, 2004). Therefore, they are 50% more efficient when measuring the energy inputs needed for each person kilometre travelled. Two other assumptions are that transit travel would maintain its market share relative to driving and that walking/cycling would maintain a market share equivalent to 1 km/person day.

Residential and Commercial

The residential and commercial sector simulates energy use by households, businesses, and institutional buildings. Together, they emitted 20% of GHG emissions and consumed 24% of final energy in 2005. The largest share of both energy consumption and emissions was from the residential sector.

The sector models are based on the Ontario models from CIMS Canada. This is a significant assumption because much of the energy use in these sectors is for space heating and cooling. Therefore, I assumed the heating and cooling load of the buildings in the TE is the same as in Ontario. Ontario has a continental climate and although the study area is a large and climatically diverse area, the majority of the population lives in a continental climate as well. Therefore, it is reasonable to assume the heating and cooling loads would be similar in both regions.

Floorspace (m^2) data are unavailable for both sectors, so I had to derive approximate values that I adjusted while calibrating the model. For the commercial sector, I modelled the floorspace by comparing the GDP of Canada with the GDP of Russia in the year 2000 and assumed the ratio between the Canadian floorspace and the TE floorspace would be the same as the ratio between the GDPs. For the residential sector, I used data showing the number of rooms per home and number of homes in both Canada and in the TE. By comparing Canadian data with data from the study region, I was able to produce a reasonable approximation of the floorspace in the TE.

The output forecast for the commercial sector uses the EIA assumed growth rate to 2025 (EIA, 2007b) after which I linked output to the rate of GDP growth to 2050 used by POLES (EC, 2006). The data available for the residential sector allowed me to produce a forecast to 2020. I extrapolated the forecast linearly to 2050. This extrapolation resulted in a slow increase in housing stock during the model run, which is consistent with the forecast of slow population decline and increasing per capita GDP used throughout the model.

While I had no technology specific data for the commercial sector, I was able to assign market shares based on the sector's fuel consumption for the year 2000. This is in contrast to the residential sector where I had forecasts of the amount of energy services used in homes, such as appliances and electronics. These forecasts were available to 2015 and sometimes 2020. In general, the demand for these energy services is lower in the TE than in Canada, however, after 2020, I assumed the demand would rise to the Canadian values by 2050.

District Heat

I altered the residential model structure by including district heating (DH), a heating method that involves the delivery of steam and hot water to homes through a distribution system. Centralized heat plants, combined heat and power plants, and industrial processes supply heat to this network. DH represents 38% of final energy consumption in the residential sector (IEA, 2004a) making it significant to the energy consumption and emissions forecasts of the study area. While DH can be a very efficient way of providing space and water heating, it is currently extremely inefficient in the TE. Because of aging infrastructure and historically low energy costs, the system losses are up to 50% of the energy input (IEA, 2004a). Since the future of DH will be significant to the TE's energy consumption, I felt it was essential to include it in the model.

Currently, CIMS-TE includes DH technologies for residential space heating, fuelled with steam supplied by boiler and cogenerator technologies copied from the industrial sectors. The DH technology competes against furnaces and electrical space heating, using a distribution technology that represents the condition of the steam pipes and transfer stations. The distribution technologies range from grossly inefficient, with 50% losses, to highly efficient, with only 5% losses. Due to additional modelling challenges, DH does not service hot-water heating or the commercial sector. Although it is used widely for both these applications, the energy consumed is small relative to residential space heating. A large effort to add DH for hot water and commercial heating would have had only a small effect on the forecasts of CIMS-TE.

Electricity

The electricity sector is among the largest energy consumers and GHG emitters in the TE. In 2005 it consumed over 14 EJ, or 32% of final energy consumption, and it emitted 20% of the GHGs in the region. The discrepancy between energy consumption and GHG emissions is due to the hydroelectric and nuclear power facilities that are common in the study area and that emit no emissions for the energy they consume. The base year output data are from the IEA and the output forecast uses the POLES reference case rate of growth (EC, 2006), although electricity production varies depending on demand within the model.

Although detailed data on fuel consumption within the sector were available, there were no specific technological data showing what types of power plants used the fuel. My assumption was that electricity generation technologies are similar around the world, so the existing technologies in the Canadian model would be suitable for CIMS-TE. I gave market share to the least energy efficient technologies available in CIMS, consistent with the high energy-intensity of the region. Thus, the main challenge was to disaggregate the IEA data into base/shoulder/peak-load detail. In this case, I kept the ratio of these loads the same as in CIMS Canada. Based on the type of technology used to generate electricity, I allocated it into one of the three loads:

- Nuclear power is used only for base load.
- All renewable energy is base load, allocated to biomass or waste combustion technologies.
- Hydro power is split among the three loads according to the Canadian ratio.
- Natural Gas power is also split among the loads at that same ratio.
- RPP is used only for shoulder and peak loads.
- Coal is used for base load and shoulder load.

These assumptions are consistent with the price and quantities of fuels in the TE. For example, natural gas is often used for peak and shoulder-loads since the infrastructure is cheap, yet the gas itself may be very expensive relative to other fuels. However, natural gas is cheap and plentiful in Russia (EIA, 2007a; Rafaj and Kypreos, 2006), so I assumed it would have a larger share in base-load power than it might elsewhere in the world.

In CIMS, the hydroelectric, nuclear, and carbon capture and storage (CCS) technologies typically have constraints that keep their respective market shares realistic. The barriers that inhibit their development can be either political, as in the case of nuclear power, physical, as they could be for CCS, or both, as in the case of hydroelectric developments that require the right geographical features and the political will to use those features for electricity generation. The EIA predicts investments in nuclear power in Russia should double through 2008 from 2005 values. As well, hydropower in the eastern portion of the TE will become increasingly important as Russia uses more of its fossil fuel resources for export (EIA, 2007a). Therefore, it is reasonable to expect strong growth in hydro and nuclear power capacity. I set the maximum possible share of hydropower to 15% of installed capacity and the maximum share of nuclear power to 35%, such that neither energy source would produce more electricity than the upper limits that Rafaj and Kypreos (2006) estimated in their modelling of this region.

Limits on CCS are most applicable in the electricity sector because this is where the technology is used first and most extensively during the simulation. The amount of CCS that can occur may be constrained by the physical size of the available storage reservoirs. However, due to the abundance of these reservoirs in the TE, CCS is not constrained in the model.

Carbon storage can occur in depleted oil fields and deep saline aquifers, which account for roughly 10% and 90% of global storage capacity respectively (IPCC, 2005). Storage in oil reservoirs is already a commercialized method. Worldwide, oil reservoirs should hold a minimum of 700 Gt of CO_2 (IPCC, 2005) and the TE contains a large amount of this storage potential (IEA, 2004b). Because 15% of global oil reserves are in the TE (IEA, 2004b), I assumed that 15%, or 106 Gt, of the storage would also be in the TE. This capacity provides ample storage for 100% of the TE's CO_2 emissions from now until 2040. If saline aquifers in the TE figure into the calculation of CCS potential, there is enough capacity to store the study area's CO_2 for several centuries.

Industry

The industrial sector is large and varied, accounting for 23% of final energy consumption and 26% of total emissions in the TE for the year 2005. Forecasts of industrial output were not available, but historical output data from the years 2000 and 2005 exist for all industrial subsectors. Furthermore, the data covered the outputs of major processes within each subsector, such as the quantities of glass versus cement produced in the industrial minerals subsector or the various types of metals produced in the metal smelting subsector. These data were not technologically explicit, so I had to allocate market share to technologies based on the low energy efficiency and the historical fuel consumption in the industrial sector. Data covering disaggregate energy consumption from 2004 confirmed that the industrial subsectors in CIMS-TE were using approximately the right amount of energy (Table 4). All other parameters in the industrial sector are directly from CIMS Canada and the validity of these parameters relies on the assumed similarity between equivalent industrial processes around the world.

Table 4: Industrial sector energy consumption (EJ)

	IEA low range[b] 2004	IEA high range[b] 2004	TE 2005	% of total
Chemical products[a]	0.83	1.05	1.05	*0.10*
Iron and steel	3.11	3.73	3.19	*0.31*
Industrial minerals	0.62	0.85	0.82	*0.08*
Pulp and paper	0.03	0.14	0.21	*0.02*
Metal smelting	0.86	0.95	0.86	*0.08*
Mining	1.20	1.35	1.20	*0.12*
Other manufacturing and non-specified	2.51	3.11	3.02	*0.29*
Total	8.50	11.06	10.35	*1.00*

[a] Excludes feedstock use.

[b] Source (IEA, 2007).The IEA data cover two regions, central/eastern Europe and the Former Soviet Union. A portion of the former region is in the TE and the entire latter region is in the TE. The low range value implies only the energy in the former Soviet Union is consumed in the TE. The high range value implies that the energy of both IEA regions is consumed within the TE.

To produce output forecasts, I made the subsector outputs grow at the same rate as the GDP forecast. Thus, a significant proportion of the energy consumption and GHG emissions forecasts are contingent on a future that includes strong economic growth coupled with strong industrial growth.

The two most important industrial subsectors are iron and steel and other manufacturing, which account for almost 14% of the study region's final energy consumption. The iron and steel subsector includes an open-hearth furnace technology for steel smelting. This older technology produced 30% of the steel in the TE in the year 2000 and consumes 33% (5-7 GJ) more energy per ton of steel than does the standard furnace technology in CIMS (IEA, 2007; International Iron and Steel Institute, 2007). Almost no data were available for the other manufacturing subsector. The shares of each major process within the sector and the technologies in use are from CIMS Canada and the sector stock is based on the amount of energy assigned to the sector during calibration. The result is a vague representation of one third of industrial energy consumption, or 7% of the TE energy consumption and 5-7% of annual emissions over the model run.

The other major change I made in the industrial sector was to the chemical products subsector. While this subsector does not consume as much energy as other manufacturing or iron and steel, it is still responsible for a comparable share of the TE's GHG emissions due to process emissions rather than combustion emissions. I added the production of soda ash and industrial gasses (e.g. O_2, N_2, acetylene) to the chemical products sector because they are produced in significant quantities within the study area (United Nations, Dept. of Economic and Policy Analysis, Statistical Divison, 2003). Soda ash production is very energy intensive and requires the combustion of fossil fuels with high carbon contents (IEA, 2007). Furthermore, the CO_2 process emissions released during soda ash production make it a significant GHG emitter, but also create an opportunity for GHG mitigation. Industrial gas production is also an energy intensive process. It accounts for roughly 20% of the subsector output in the TE, it its share is expected to grow over the coming decades.

Energy Supply

Russia and several other TE nations are significant energy producers and will export large quantities of oil and natural gas during the simulation period (EIA). Accordingly, the energy supply sector is responsible for 12% of final energy consumption and 19% of GHG emissions in the TE in 2005. The most important subsectors within the energy supply sector, based on GHG emissions, are natural gas extraction, followed by petroleum crude and then petroleum refining. Comparatively, coal mining is an insignificant energy consumer and GHG emitter.

The structure of the natural gas subsector is based on the CIMS Alberta model. I assume there is a 20% loss of gas from the well to the market and the same ratios of sweet to sour gas plants as in Alberta. The technologies with the fewest pollution controls dominate the stocks in this sector. The exceptions to this assumption are the compressor engines that transmit natural gas through pipelines. I allocated some of the base-year market share to the more efficient electrical engines in addition to the natural-gas-fuelled engines to match historical fuel consumption by this sector[3].

Russia has the largest natural gas reserves in the world and is the world's largest gas exporter (EIA, 2008), hence the natural gas subsector output continues to grow during the entire simulation. I used the EIA natural gas production forecast to 2030 (EIA, 2007b) and the POLES rate of growth for production from 2030 to 2050 (EC, 2006). The production forecast I used keeps total production well within the estimated resource by 2050 (Table 5). Because of the abundant natural gas reserves, I assumed that negligible coal bed methane would be produced within the TE by 2050.

Table 5: Fossil fuel reserves and production (10^9 m^3)

	Proven Reserves	Estimated + Proven Reserves	CIMS TE total production by 2050
Natural Gas	55000	100000	65000
Conventional Oil	16	40	40

Source: (EIA, 2007b; EIA, 2008; USGS International Minerals Statistics and Information, 2007)

I also used the EIA production forecast to 2030 (EIA, 2007b)and the POLES rate of growth for production of crude oil from 2030 to 2050. Although Russia's oil reserves are the eight largest in the world (EIA, 2007a), production is forecasted to decline from 2030 onward (EC, 2006; EIA, 2007b). The CIMS-TE output forecasts bring the modelled production of crude oil very close to the total estimated reserve. Therefore, by using these production forecasts, I am assuming that the estimated reserves are actually available and in a large enough quantity that oil production only experiences a slow decline rather than a rapid crash.

Due to a lack of data and information, I have not included unconventional oil production in the model, although there is approximately 7.5 billion m^3 of heavy oil and bitumen that is technologically recoverable (USGS International Minerals Statistics and Information, 2007). While the large conventional oil reserves in the TE could delay the exploitation of unconventional oil until later in the model run, future refinements of the

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[3] See appendix B for an explanation of how the energy consumed by pipelines was calculated from the transportation sector calibration data.

model should update this assumption if the applicable forecasts become available. I have assumed that 10% of oil production happens offshore, based on a rough survey of where the region's oil reserves and active oil fields are (EIA, 2007a).

The coal and refinery sector outputs are based on IEA production data (IEA Statistics, 2003b). The models are copies of the CIMS-Canada models with different output forecasts. I made one exception to this methodology. Using the available data, I calculated the refinery gain, or change in volume from crude oil to finished product. This is an important parameter because it determines the total oil throughput needed to produce the petroleum-based fuels available in CIMS-TE and, hence, has an effect on the price and quantity of these fuels.

CHAPTER 4: RESULTS

This chapter begins by showing which carbon price-paths achieved the policy targets established in chapter 2. It then presents the results of the BAU simulation and the policy simulation that achieved the targets. These results will provide an understanding of how the sectors respond to the GHG price and how the policy affects fuel consumption and total final energy consumption. Using wedge diagrams and marginal abatement cost curves, I illustrate how the emissions are reduced and the quantity of emissions reduced at specific GHG prices. The chapter concludes with the results of the sensitivity analysis, exploring uncertainty in the rate of industrial growth and in the cost of carbon capture and storage.

GHG Emissions and Energy Consumption

Effect of the GHG Prices

I examined how the carbon price-paths I applied achieved the policy targets described in chapter 2. The first target was a 50% regional reduction in GHG emissions from the year 2000 and the second target was based on the contraction and convergence policy where global emissions would also be 50% below the year 2000 levels but all regions would have equal per capita emission. For this latter target, the TE would have to reduce its emissions by 84% from the year 2000.

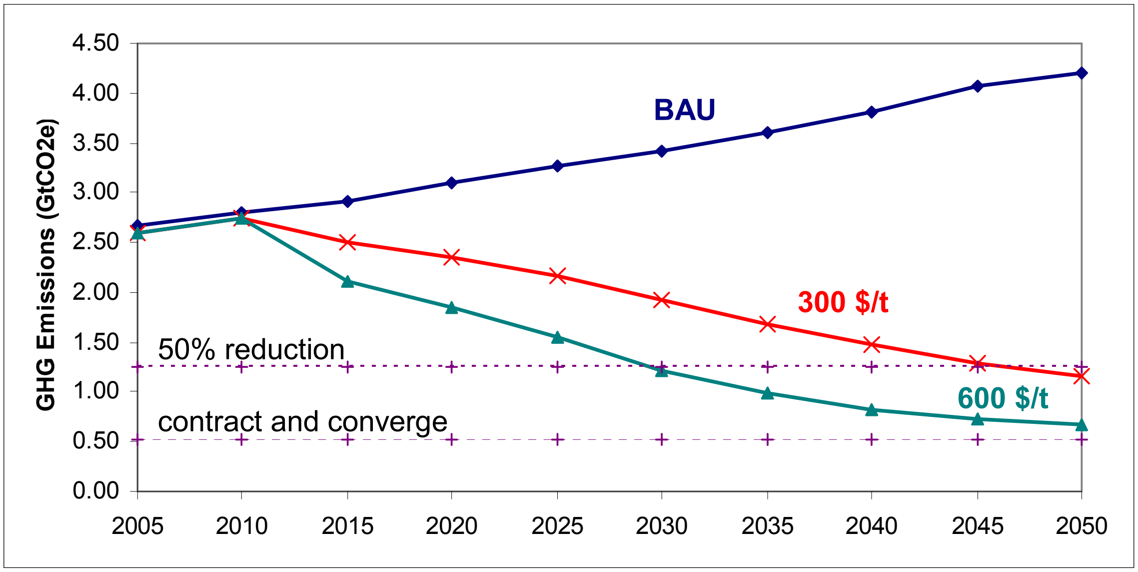
The price-path that rose to 300 $/tCO_2e$ by 2050 achieved the 50% regional reduction, while none of price-paths achieved the contraction and convergence target. Even a tax of 600 $/tCO_2e$ only reduced emissions 73% below 2000 (Table 6, Figure 4), falling 7% short of the goal. This large carbon price resulted in annual emissions of 0.67 $GtCO_2e$, still larger than the 0.52 $GtCO_2e$ needed to achieve the contraction and convergence target. As stated previously, CIMS-TE may not fully capture the effect of extreme carbon prices. However, these prices demonstrate how difficult it would be for the TE to achieve deeps emissions reductions using current and emerging technologies.

Table 6: Effect of carbon price on GHG emissions

	GHG Emissions Price in 2050 ($/t CO_2e)[a]						
	50	100	150	200	250	300	600
% relative to 2000 emissions in 2050	+24%	-2%	-19%	-37%	-46%	-53%	-73%

[a] All prices are in 2005 US dollars.

Figure 4: BAU and Policy Emissions



For the remainder of my report, I will analyse the carbon price-path that reduced emissions 50% below the year 2000. I will refer to the results of this GHG price-path that reached 300 $/t$CO_2$e by 2050 as the policy forecast.

Energy Consumption Forecasts

Despite the large difference in emissions between the BAU forecast and the policy forecast, the total final energy consumption of the forecasts differ by only 12% in 2050 (Figure 5 and Figure 6). Under the BAU forecast, energy consumption in 2050 rises by over 75% to 78 EJ, while under the policy forecast, energy consumption rises to 69 EJ. Although total final energy consumption is similar in both forecasts, the fuel mixes are quite different, as are the sectors that drive the increase in energy consumption.

Figure 5: Total primary and secondary energy consumption by fuel

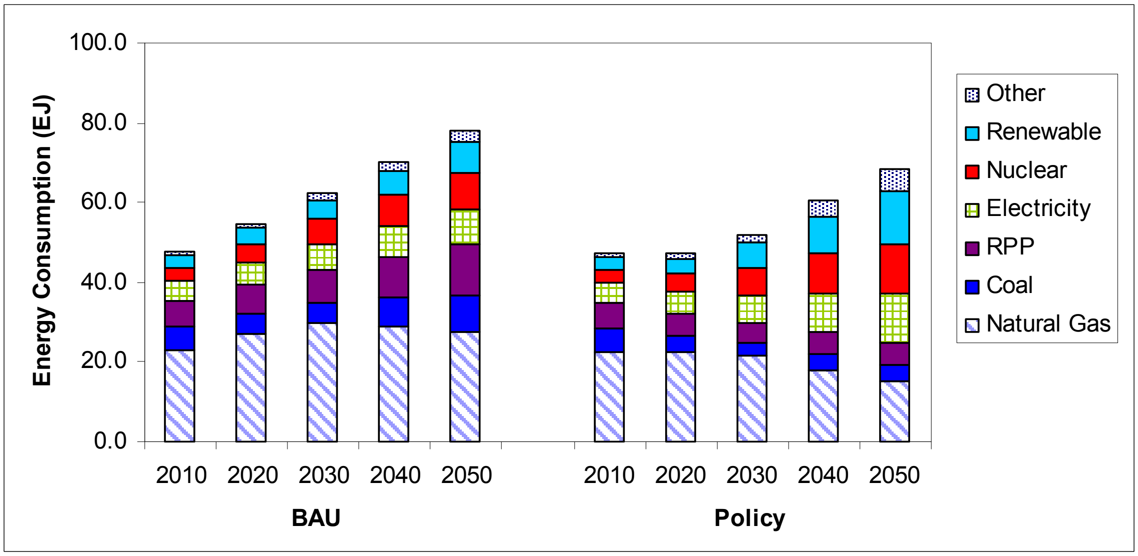
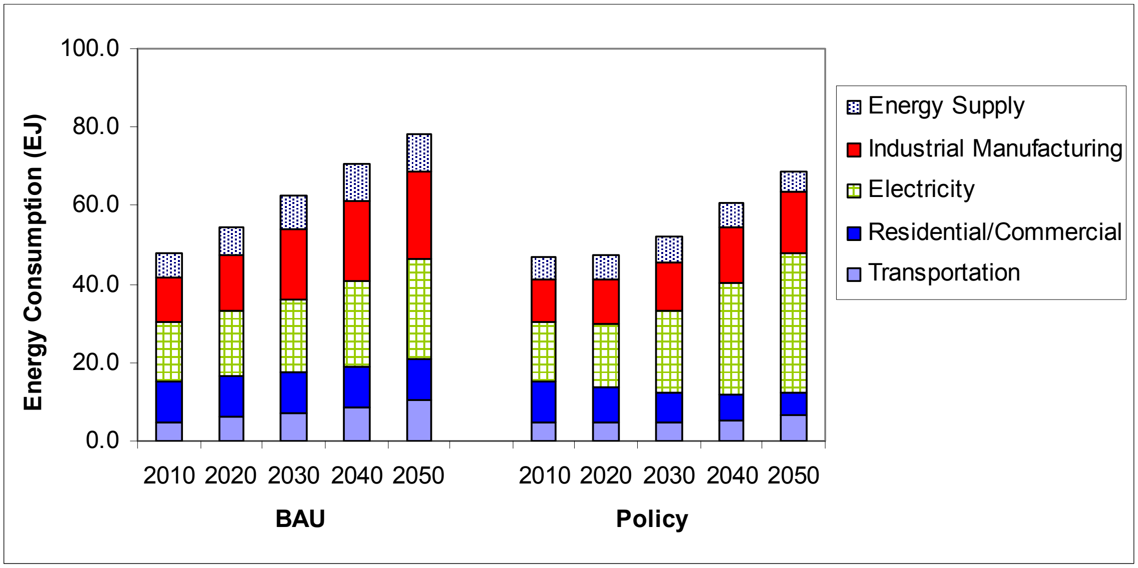


Figure 6: Total primary and secondary energy consumption by sector



BAU

In the BAU forecast, renewable and nuclear fuels increase in importance as additional hydroelectric and nuclear capacity comes online (Figure 5). Nonetheless, fossil fuels account for 64% of final energy consumption by 2050. Natural gas alone accounts for almost half of all final consumption. This fuel share drops slightly during the model run as the price of natural gas rises relative to other fuels. Coal and RPP make slight increases in their fuel share by 2050 as the industry and transportation sectors increase their energy consumption (Figure 6).

The rise in energy consumption in the BAU forecast is driven by the industrial sector and the electricity sector (Figure 6). By 2050, they are responsible for 36% and 32% of the increase in energy consumption respectively. Energy consumption in the energy-supply sector and transportation also increase somewhat as their output rises. Residential and commercial energy consumption remains almost level because market pricing of energy induces efficiency gains that offset the increase in floorspace demand.

Policy

In the policy forecast, fossil fuels fall to 36% of the fuel share by 2050 (Figure 5). Half as much fossil fuels are consumed in the policy forecast as in the BAU forecast, but these fuels still remain an important energy source, even under a high GHG price. Natural gas continues to be abundant relative to other fuels throughout the simulation, representing 22% of total final energy consumption. Natural gas accounts for 61% of the fossil fuels consumed in 2050 under the policy forecast, as opposed to only 55% of fossil fuels under the BAU forecasts. However, because the consumption of fossil fuels declines under the policy, the total quantity of gas consumed in 2050 is 40% less than in the BAU forecast. Overall, fossil fuels are still significant in the policy forecast, but their consumption falls and natural gas displaces fossil fuels that emit more GHG per unit energy.

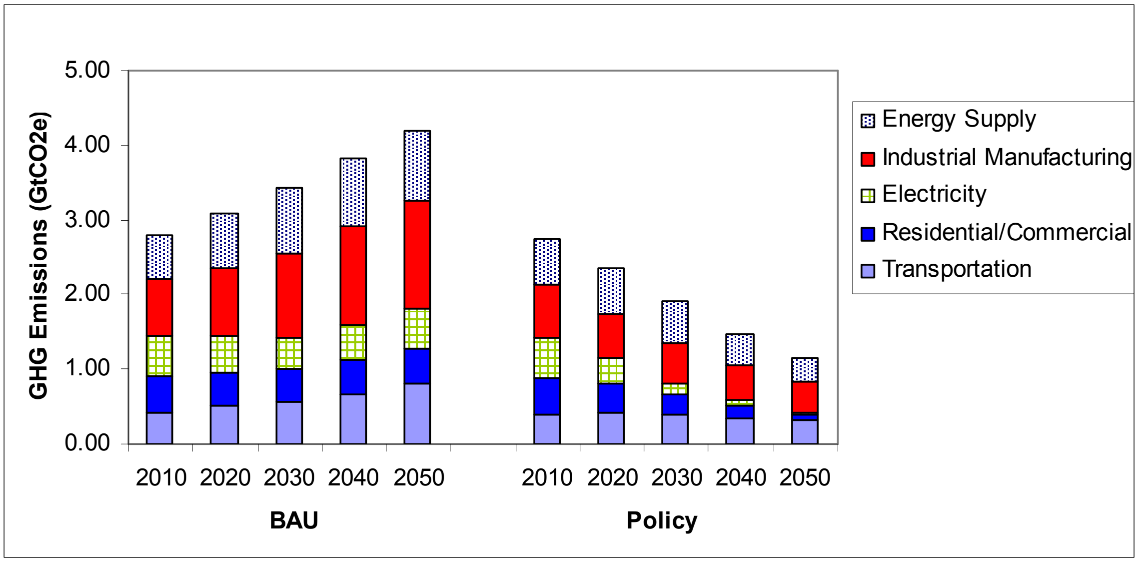
In place of fossil fuels, the policy forecast indicates that electricity consumption will nearly triple by 2050. A small increase in nuclear power partially fuels the additional electricity production such that 33% more nuclear energy is used in the policy forecast by 2050 than in the BAU forecast. The rest of the electricity generation is supplied from a doubling of hydroelectric capacity by 2050 compared to the BAU forecast and a slight increase in the use of biomass combustion and wind energy.

Because of the additional demand for electricity in the policy forecast, the electricity sector contributes greatly to total final energy consumption. By 2050 this sector consumes 36 EJ, or 53% of final energy consumption and it responsible for 75% of the increase in energy consumption from 2000 (Figure 6). Industrial manufacturing accounts for nearly 17% of the increase in energy use. In contrast, the energy supply sector and transportation sector show only slight increases in energy consumption, due to reduced sector output and increased efficiency relative to the BAU forecast. For the same reasons, the residential and commercial sectors also have significantly reduced energy consumption by 2050.

BAU Emissions Forecast

The BAU forecast shows GHG emissions rising to just over 4 GtCO$_2$e per year in 2050 (Figure 7). Emissions from the transportation sector increase in response to the forecasted rise in transportation demand, driven by growing affluence in the TE. On the other hand, emissions from the residential and commercial sector remain almost constant during the model run. In part, this is due to improved energy efficiency of building shells, retirement of decrepit district-heat systems, and an increase in the use of electricity in the residential and commercial sectors. The slowly declining population also offsets the emissions caused by the rise in per capita floorspace demanded in this sector. In the electricity sector, the emissions do not rise as quickly as the output, as more zero emissions technologies such a nuclear energy and hydroelectricity are added to generating capacity. Additionally, old thermal power plants are replaced with modern and more efficient plants as energy prices rise and technologies are retired.

Figure 7: GHG emissions by sector



The energy supply sector and the industrial sector are responsible for the majority of GHG emissions in the BAU forecast (Figure 7). The increase from the energy supply sector is a result of countries in the TE, especially Russia, exploiting their energy resources and increasing their exports of oil and natural gas. While the exact amount of fossil fuels that will be extracted is unknown, I assumed that the international demand for these fuels would remain strong in the absence of GHG mitigation policies.

The largest increase in BAU emissions comes from the industrial sector and this increase is driven by the exogenous output forecasts of the industrial subsectors. Recall that I linked these forecasts to a forecast of GDP growth, assuming that industrial activity would remain tightly coupled with economic activity. I believe, however, that the future relationship between GDP and industrial output is uncertain.

Policy Emissions Forecast

By 2020, the policy forecast shows a 24% drop in annual emissions from the BAU forecast. By 2050, emissions fall to 1.16Gt/CO_2e per year (Figure 7), roughly 50% below annual emissions in 2000. Emissions from the transportation sector remain stable due to improvement over BAU energy efficiency, a drop in freight transportation demand, and some switching from fossil fuels to biofuels late in the model run. The electrical sector emits almost no GHG by 2050. This drop in emissions is due to a huge uptake of carbon capture and storage (CCS), as well as some fuel switching to nuclear, hydroelectricity and biomass. The residential and commercial sectors also have a dramatic drop in emissions by 2050, primarily due to fuel switching to electricity and enhanced by accelerated improvements in energy efficiency.

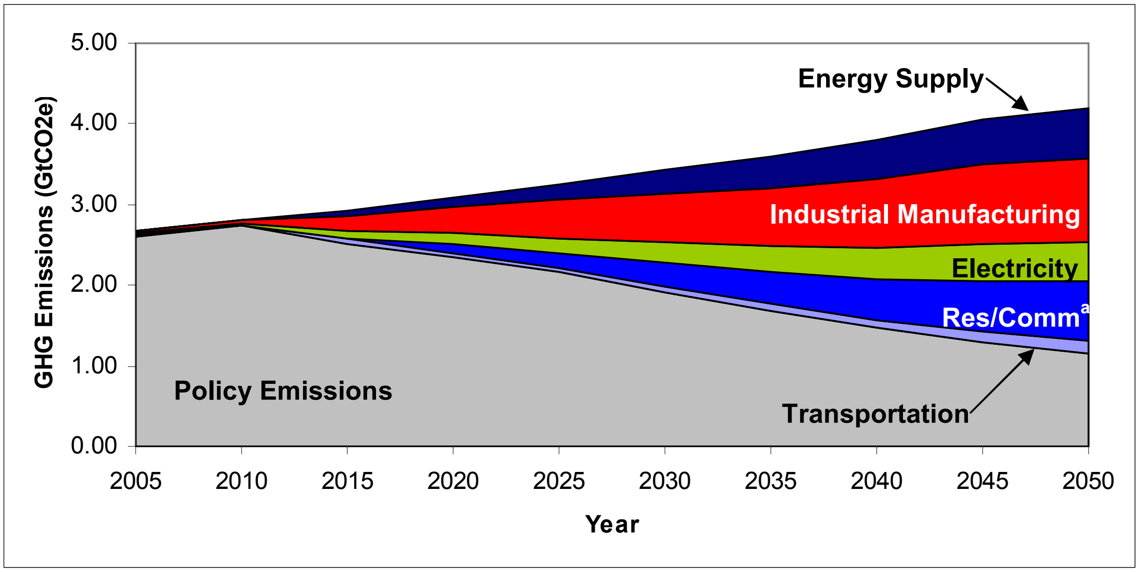
The energy supply sector and industrial sector show trends similar to the BAU forecast. These two sectors are the drivers of emissions growth in the BAU forecast and remain so in the policy forecast. Although their emissions fall, these sectors are still the two most significant emitters by 2050. In the industrial sector, CCS drives the decline in emissions below BAU levels after 2020. This abatement method is responsible for 42% of the difference between the BAU emissions and the policy emissions for this sector. For energy supply, GHG controls, such as the prevention of methane leaks during fossil fuel extraction, were responsible for 30% of the avoided emissions. Equally important was the drop in output that CIMS-TE forecasts for these sectors. While the other sectors see output drops from 14-17% relative to the BAU, output in the energy supply sector changes more dramatically. Natural gas extraction sees the largest output change in 2050, falling 30% below the BAU output in response to the increased cost of production and reduced demand within the TE.

Method and Cost of Policy GHG reductions

Analysis of GHG reductions

Wedge diagrams summarise the comparison between the BAU and policy emissions forecasts. Figure 8 displays the contribution that each sector makes to emissions abatement in the TE over time. While industry was the largest emitter over the model run, it was also the largest source of emissions reductions. However, to interpret this graph, one must remember that abatement from a sector can only be as high as the emissions from that sector. For example, electricity appears to contribute very little to abatement, but it had few emissions in the BAU forecast. Therefore, the sector can contribute less to the total GHG abatement.

Figure 8: Wedge diagram by sector

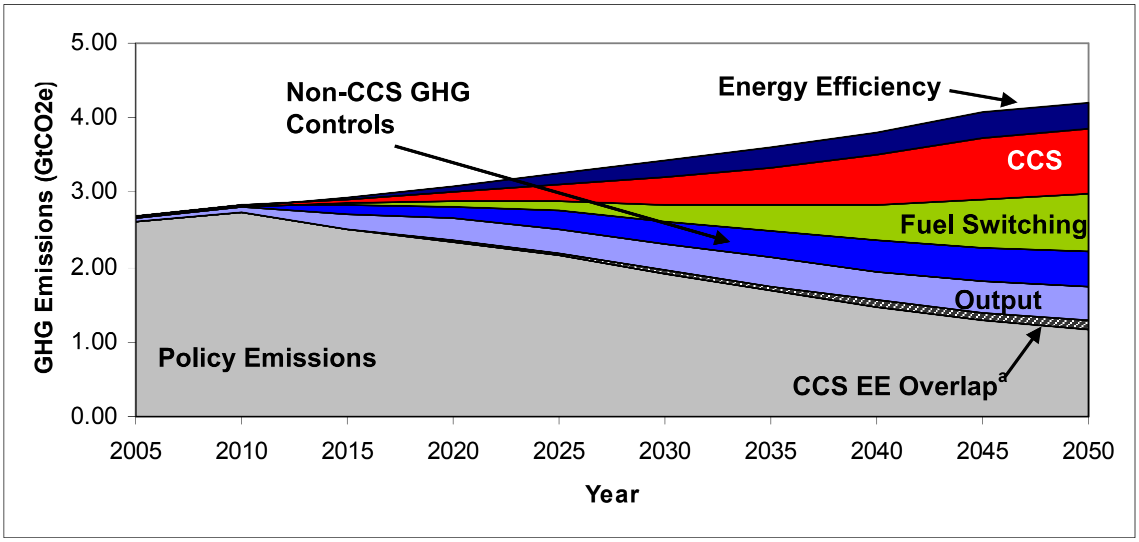


[a] Res/Comm is the residential and commercial sectors

Figure 9 summarizes the actions that will be used to reduce GHG emissions. Energy efficiency plays a minor role in reducing emissions, yet it is still an important abatement option in the transportation sector and is somewhat important in the residential and commercial sector after 2030. However, prior to 2030, efficiency improvements in the BAU forecast are driven by the decline of energy subsidies and the rise of energy prices. The additional price signal from the policy provides few incremental improvements in energy efficiency from 2005 to 2030.

Compared to energy efficiency, carbon capture and storage (CCS) plays a much larger role in emissions reduction. This abatement method is responsible for one third of the avoided emissions in 2050. Early in the model run, CIMS-TE forecasts a limited uptake of CCS in the electricity sector, while after 2020, CCS is used more extensively in both the industrial sector and the electricity sector.

Figure 9: Wedge diagram by abatement action



[a] CCS EE Overlap represent the abatement lost by reduce energy efficiency when CCS is used

Table 7: Contribution of abatement actions to policy emissions forecast

Abatement Action	Energy Efficiency[a]	CCS	Fuel Switching	Non-CCS GHG Control	Output Change
Annual GHG reduced ($GtCO_2e$ in 2050)	0.41	0.92	0.78	0.48	0.45
% annual GHG reduced	13	30	26	16	15

[a] The CCS EE overlap is share equally among energy efficiency and CCS

Table 7 shows the contribution of each abatement action in 2050. CIMS-TE forecasts fuel switching to be the second most important abatement action after CCS, accounting for 26% of the avoided emissions. The majority of fuel switching was to electricity from fossil fuels within the commercial and residential sectors and to hydroelectricity from fossil fuels in the electricity sector. The model also forecasts some uptake of biomass and biofuels in the transportation and electricity sectors late in the model run. Fuel switching was less important in the energy supply sector and the industrial sector, in part because these sectors already use natural gas for applications that require fossil fuels. Therefore, they could not switch to a fossil fuel with fewer GHG emissions and using biofuels was either not possible or not economical under the policy.

As well, several processes, such as iron smelting and cement manufacturing, require the use of carbon rich fuels and cannot use natural gas or electricity.

Non-CCS GHG controls reduce GHG emissions other than CO_2, such as methane and nitrous oxide, and are responsible for 16% of the emissions reductions in 2050. CIMS-TE forecasts the use of this abatement action only in the energy supply and industrial manufacturing sectors because this is where the majority of non-CO_2 emissions occur in the TE. These controls include the prevention of methane venting during fossil fuel extraction or the destruction of process gases released by metal production.

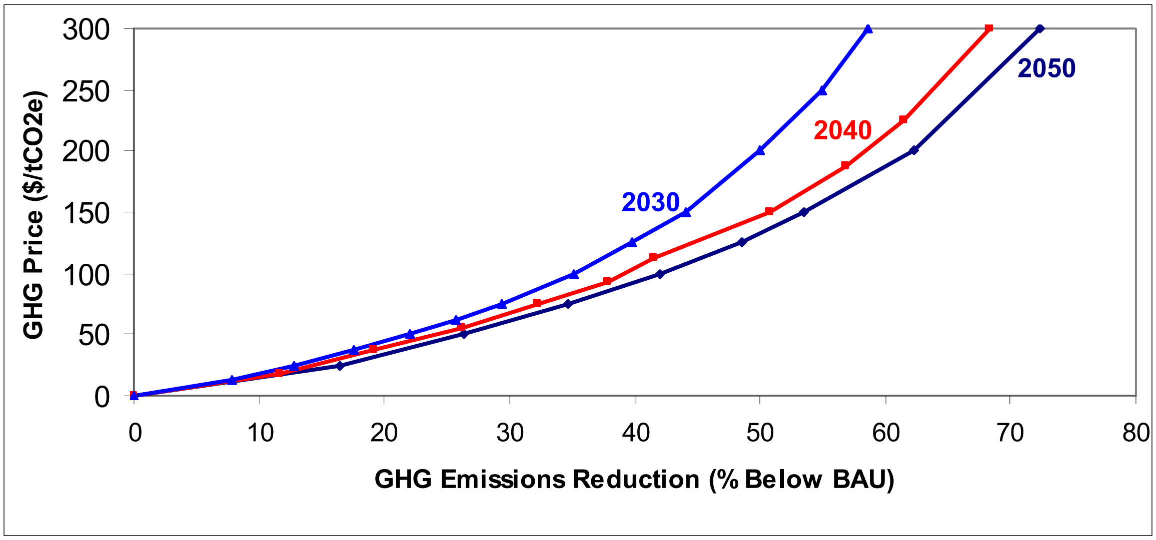
Finally, sector outputs fell by roughly 15% relative to the BAU, accounting for 15% of the emissions reductions by 2050. Until 2020, output change is the primary abatement method, especially in the energy supply sector. Presumably, a drop in output could also indicate a loss of jobs and a reduction in goods and services available for consumption, thereby reducing welfare in the study area. While the output change is significant, this is not necessarily an indicator of how welfare may have changed. CIMS only models the energy intensive sectors of an economy and this simulation did not include any recycling of the revenue collected from the GHG tax, nor does it model changes in investments. Depending on how this revenue re-enters the economy, it could bolster demand for the sector outputs, or encourage economic growth in non-energy intensive sectors. Thus, an output drop in CIMS-TE does not clearly indicate a decline in welfare, nor can we be sure that the output change would be as large as the model indicates.

Marginal Cost of Abatement

Using the assumption that firms and households will take all opportunities to reduce emissions that cost less than the GHG emissions price, this emissions price becomes the marginal abatement cost (MAC). The MAC is the cost to avoid emitting the next unit of GHG above what has already been abated. A MAC curve displays the costs with the corresponding amount of GHG avoided, showing the effect of a policy on either cumulative GHG emissions or GHG emissions relative to a baseline.

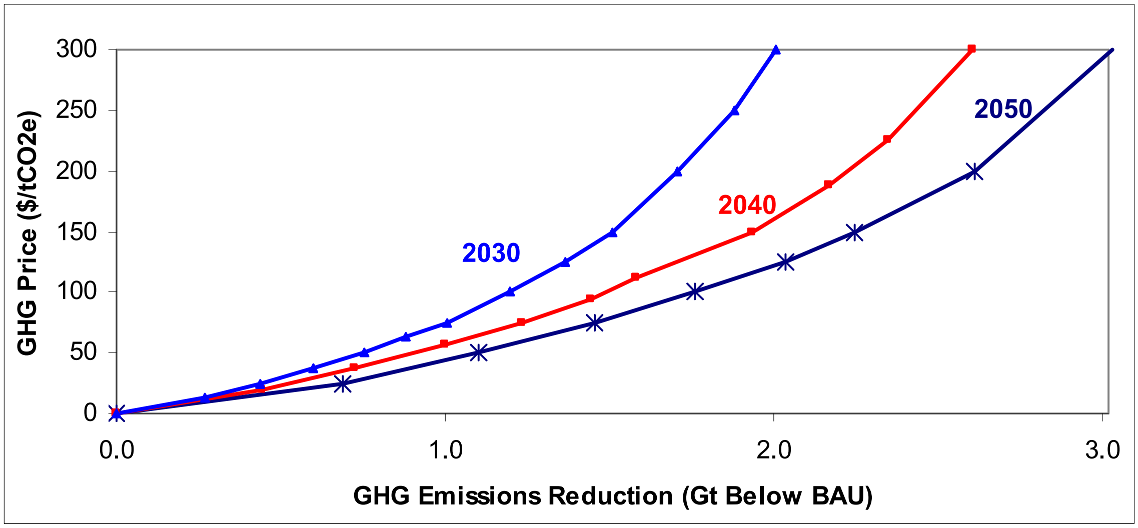
Figure 10 displays the MAC curve for the TE in three different years. The emissions avoided are in percentage relative to the BAU emissions, allowing a comparison between three time periods with different levels of baseline emissions The shallowest MAC curve showing the lowest cost emissions is from 2050, followed by 2040. The 2030 MAC is the steepest curve indicating that it is more expensive to avoid large quantities of emissions over short time periods. Greater technological change over less time incurs the cost of retiring capital stock before the end of its useful life. To replace this stock, households and firms may adopt unfamiliar, more expensive, and potentially riskier technologies, incurring a further cost. For example a drop of 50% in 2030 requires a GHG price of 200 $/tCO$_2$e, while the same reduction in 2050 only requires a price of 125 $/tCO$_2$e. Since total emissions are larger in 2050, this translates into a greater absolute reduction of 2 GtCO$_2$e in 2050 versus 1.7 GtCO$_2$ in 2030 (Figure 11). Reductions are cheaper over the long-term because they do not force early retirement of capital stock and new technologies can be adopted gradually while taking advantage of economies-of-scale.

Figure 10: Relative marginal abatement cost of GHG emissions in the TE



All prices are in 2005 US dollars.

Figure 11: Absolute marginal abatement cost of GHG emissions in the TE



In all three curves, the slope of the MAC curve increases with a larger GHG reduction below the BAU, indicating that there is reduced abatement possible at any given GHG price. However, none of the curves approaches a vertical asymptote, even when the GHG price is 300 $/tCO$_2$e. This demonstrates that there are still abatement action available, even though their cost is high.

The shape of the TE region's MAC curve is based on the MAC curves of the sectors within the region. Figure 12 and Figure 13 show the 2050 MAC curves by sector as a physical amount below the BAU emissions and a fraction below the BAU respectively. The bulk of avoided emissions come from the industrial manufacturing sector (Figure 12), as this sector emits the most GHG, giving it the largest potential for abatement. However, the cheapest abatement, based on the fraction of the sector's emissions that are avoided, comes from the electricity sector, followed by the residential and commercial sectors (Figure 13). It is interesting to note that the slope of the transportation and energy supply MAC curves remain approximately constant at higher GHG prices. Although the MAC rises for increasing abatement in these sectors, the rate of increase of the MAC does not change dramatically, indicating that further abatement would still occur at GHG prices higher than 300 $/t. The MAC curve for the electricity sector becomes vertical in Figure 12 because the sector reaches near zero emissions. At prices greater than 200 $/tCO$_2$e, the remaining emissions from this sector are what cannot be captured using CCS. To abate the final 5-10% of emissions from this sector would require a complete switch to renewable energy

Figure 12: Marginal abatement cost of GHG emissions by sector (GtCO$_2$e below BAU)

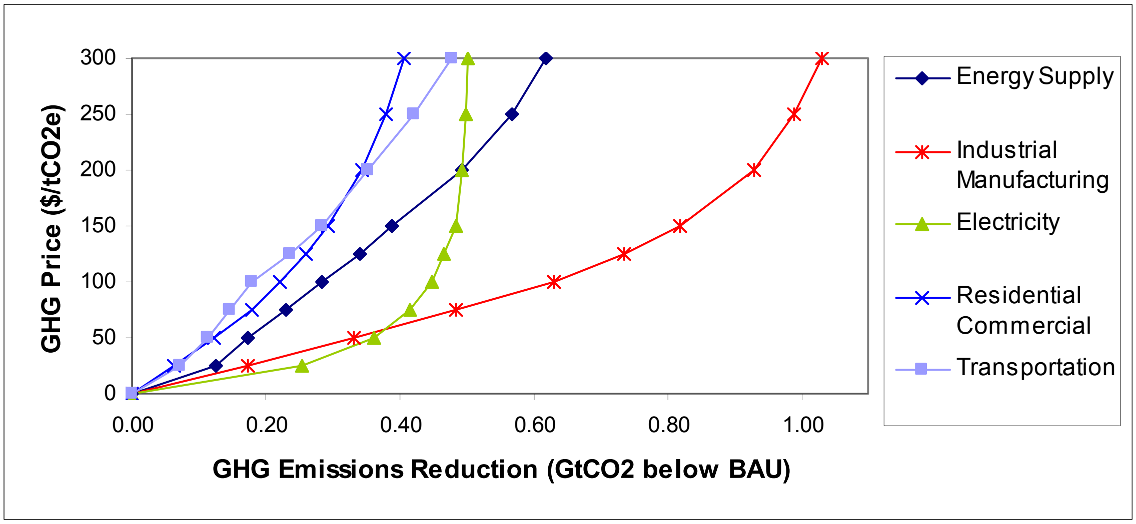
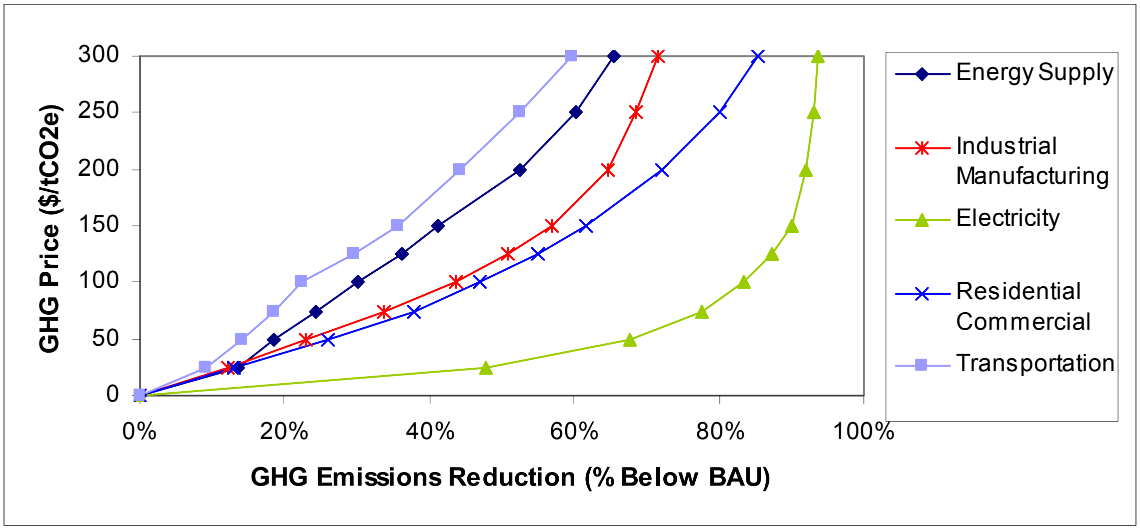


Figure 13: Marginal abatement cost of GHG emissions by sector (% below BAU)

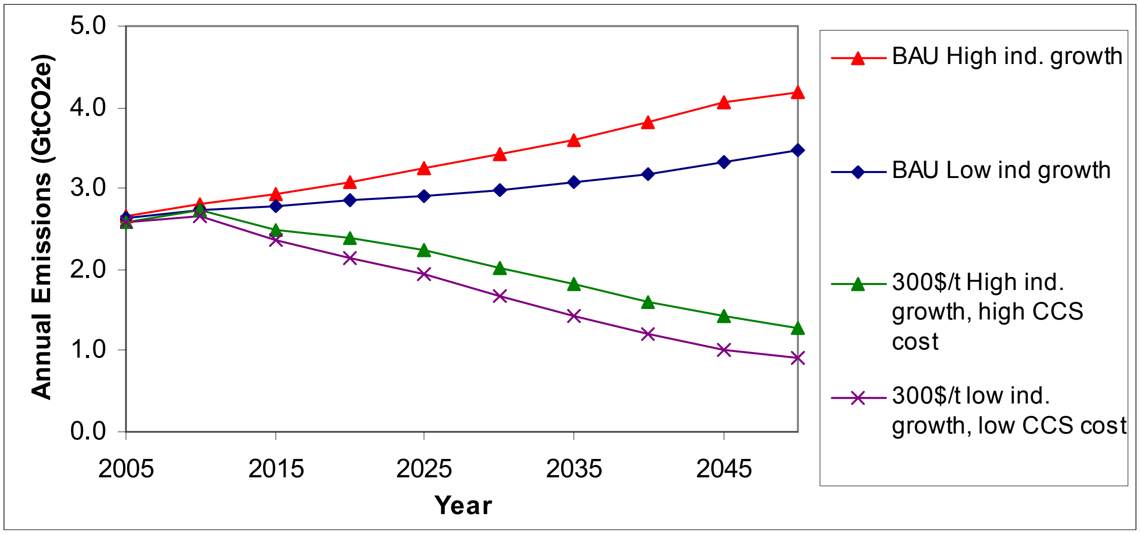


Sensitivity Analysis

In the sensitivity analysis, I studied the effect of changing the rate of industrial growth and the cost of carbon capture and storage (CCS). Both parameters are uncertain and heavily influence the policy forecast; therefore, they are important to a study of uncertainty in CIMS-TE. Even though the model cannot predict the future, it can indicate how a policy might perform under a range of future conditions. By demonstrating how robust a policy is relative to the uncertainties inherent in the model, a sensitivity analysis can provide information on the degree of confidence in the results.

Figure 14 displays the BAU and policy emissions forecasts from the extremes of the sensitivity analysis. A high rate of industrial growth raises the emissions of both the BAU and policy forecast, while a high cost for CCS raises the emissions of only the policy forecast. The BAU forecast and policy forecast vary greatly in this analysis, but how does this change affect the strength of policy that will achieve the policy target? While the forecasts of emissions in 2050 may change as parameter values change, it is most important to understand how this variation affects decision making in the present. Therefore, instead of focussing on the changes to the outcome of the policy, I studied the sensitivity of the policy needed to reach a given outcome. Thus, this sensitivity analysis examines the variation in the GHG price necessary to achieve the 50% regional reduction as the rate of industrial growth and cost of CCS change.

Figure 14: Effect of CCS cost and industrial growth on BAU and policy emissions

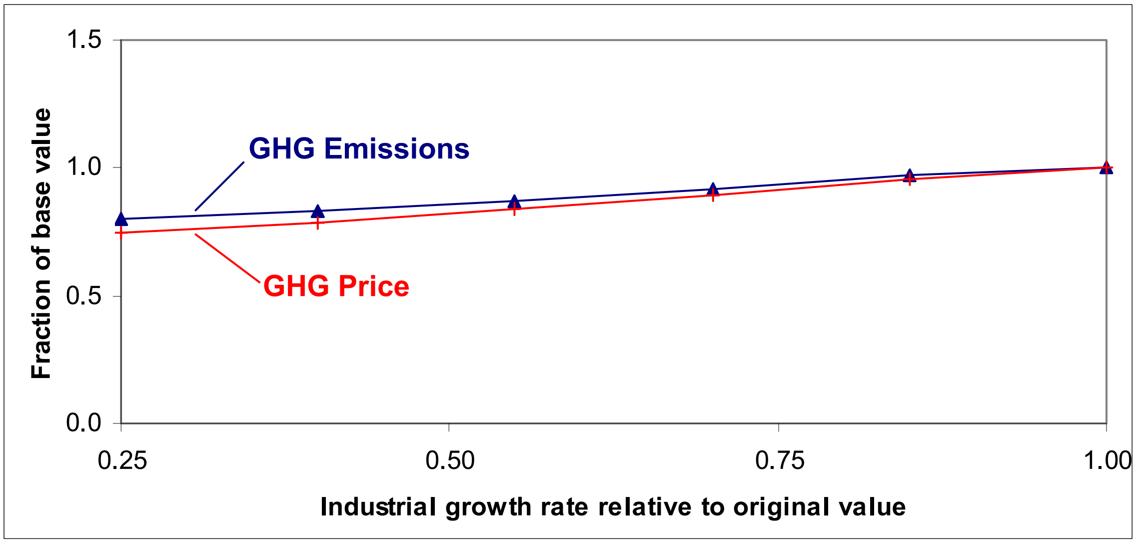


Sensitivity to Industrial Output Forecast

In my BAU and policy forecasts, the industrial sector was growing at the same rate as the GDP of my region. In this section, I explore how decoupling industrial growth from economic growth affects these results. By examining the model outputs over industrial growth rates that are equal to the GDP growth rate down to one quarter of this rate, I determined the sensitivity of GHG emissions and GHG prices to this rate.

Figure 15 displays the sensitivity of BAU GHG emissions in 2050 to the rate of industrial growth in the model. It also displays the sensitivity of the GHG price needed to reach a given level of emissions using the linear price-paths of this study. Steeper slopes indicate greater sensitivity to the parameter in question. The values in the figure are relative to their 'base values'. For example, the base value of GHG emissions is the value that CIMS-TE forecasted using my initial assumption that industry would grow at the same rate as GDP. If the rate of industrial growth drops by 75% from the initial assumption, the relative value is 0.25 and industry grows at one quarter the rate of GDP (Figure 15). The corresponding relative value of emissions is 0.8. This means a 1% drop in the rate of industrial growth causes a change in GHG emissions in 2050 that is four times smaller, or 0.25%. This relationship holds regardless of the GHG price used. However, because the GHG price changes total emissions, equal proportional changes may be different in absolute terms depending on the policy. To illustrate this with values from Figure 14, 1% of 1.28 $GtCO_2e$ is less than 1% of 4.2 $GtCO_2e$. Nevertheless, emissions are not highly sensitive to changes in industrial growth. Although, the industrial sector is a significant GHG emitter, there are several other sectors in CIMS-TE and I assume the economic growth happens in non-energy intensive sectors. The outputs of the other sectors remain constant in this analysis, so a change in industrial growth has a dampened effect on overall emissions.

Figure 15: Sensitivity of BAU GHG emissions and price in 2050 to industrial growth



Likewise, the effect of the changing rate of growth also has a dampened effect on the GHG price needed to reach a given emissions target in 2050 (Figure 15). The GHG price needed to reach a 2050 emissions target is slightly more sensitive than the rate of industrial growth. A 1% change in growth causes a 0.33% change in the GHG price and this relationship holds regardless of the target or price. Again, the fact that only the industrial sector is changing creates this dampened effect, but the sensitivity of price is higher than emissions because of sectoral marginal abatement costs (MAC). The industrial manufacturing sector has higher MACs as a % of BAU emissions (Figure 13), than both the residential/commercial sector and the electricity sector. Therefore, a reduction in emissions from industry reduces the amount of higher cost abatement and, hence, the GHG price is more sensitive than emissions.

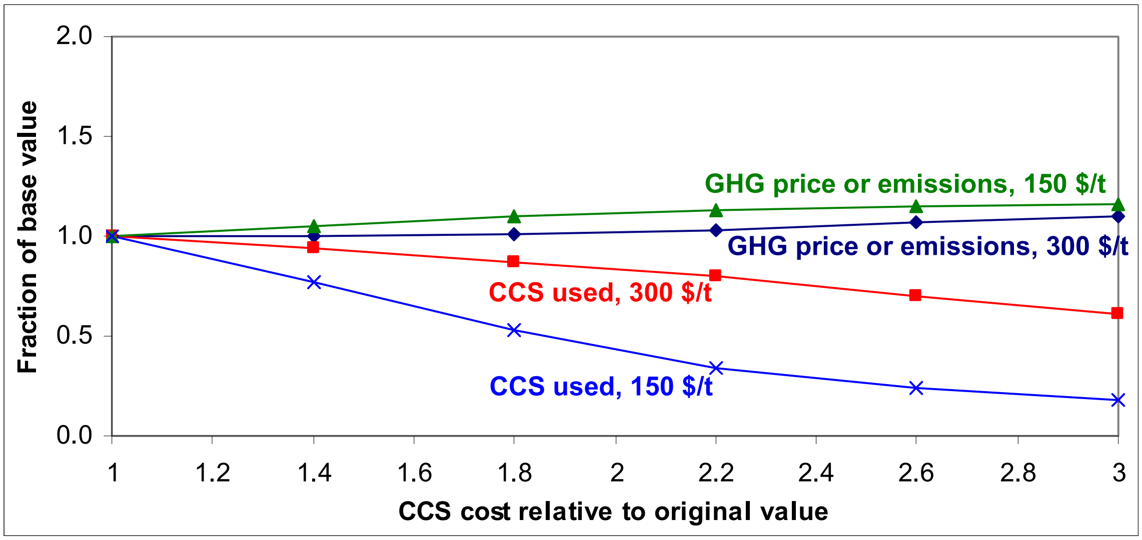
Sensitivity to the Cost of Carbon Capture and Storage

In my original BAU and policy forecasts, I used a CCS cost from the low end of recent cost estimates (Rubin et al., 2007). In this section, I explore the effect of CCS cost on the model results. By raising the cost of CCS as high as triple its base value, I studied the sensitivity of GHG emissions, GHG price, and quantity of CCS used in 2050.

Figure 16 displays the forecasted GHG emissions and the amount of CCS under various GHG prices. It also shows the sensitivity of the GHG price needed in 2050 to reach the base value of emissions. It can be read in the same way as Figure 15.

Again, all values on the y-axis are expressed in terms of their base value when the original CCS cost (1 on the x-axis) is used for the simulation. The greater the slope, the greater the sensitivity to CCS cost. Because the sensitivity changes as the GHG price changes, the figure contains information for GHG price-paths that reach 150 and 300 $/tCO$_2$e by 2050. The sensitivity of the GHG price to reach a given emissions level is the same as the sensitivity of GHG emissions. For clarity, I have omitted it from the figure.

Figure 16: Sensitivity of price, emissions, and CCS used to CCS cost (2050)



The changes to GHG price that achieve equivalent emissions reductions mirror the changes in GHG emissions. At a given price, the same line displays both the sensitivity of GHG price and GHG emissions. All values are relative to their base value in the BAU and policy forecasts.

When the GHG price reaches 300 $/tCO$_2$e by 2050, tripling the cost of CCS (3 on x-axis) only raises emissions by 10% (1.1 on y-axis) relative to the base value. Conversely, increasing the GHG price by 10% to 330 $/tCO$_2$e, stops the emissions from rising even if CCS cost triples since the change in GHG price approximates the change in emissions. This relationship does not stay constant for all GHG prices; however, emissions and the GHG price remain insensitive to the change in CCS cost. At 150

$/tCO$_2$e, tripling the cost of CCS creates a 15% change in emissions, or the GHG price must rise by 15% to stop emissions from changing.

The amount of CCS used is far more sensitive to any change in CCS cost than are the emissions or GHG price (Figure 16). If the cost of CCS triples, the amount of CCS used falls by 40-80% depending on the GHG price. The sensitivity is greater at lower GHG prices, such as 150 $/tCO$_2$e, where a 1% increase in the cost of CCS causes approximately a 0.4% decrease in the quantity. At 300 $/tCO$_2$e, the change in quantity is only 0.2% if the cost rises by 1%.

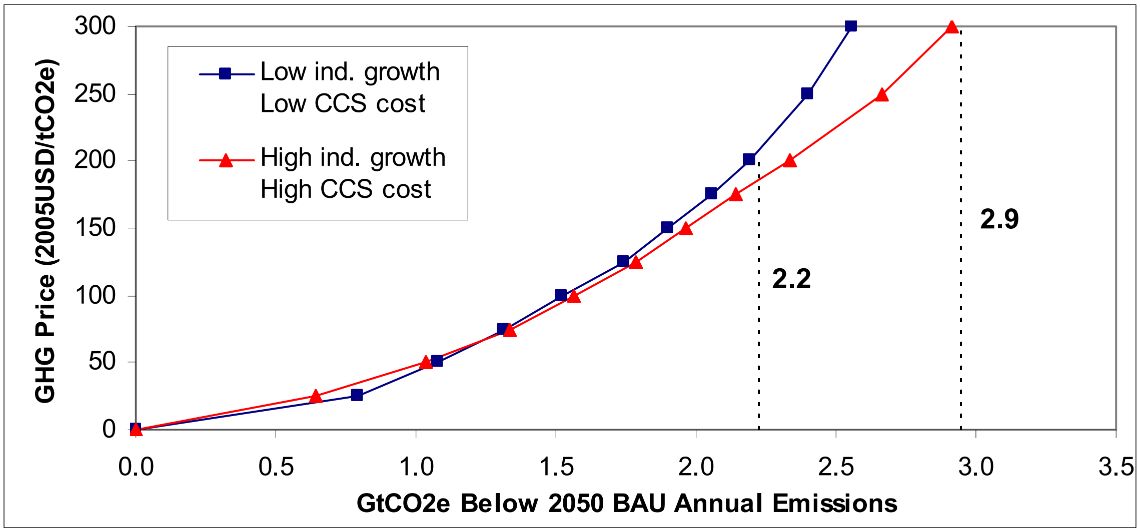
The amount of CCS used is more sensitive than the change in emissions or GHG price, indicating that there are other abatement options available in CIMS-TE that have marginal costs similar to the original cost of CCS. Even if CCS is too expensive to use, the model indicates that firms and households will find other ways to reduce GHG at a given price. These abatement options are more costly than CCS since the GHG price must increase to prevent emissions from rising as the cost of CCS also rises, but the difference is slight, roughly 10% more at high GHG prices and 15% more at lower GHG prices. The difference is more apparent at lower GHG prices because of the relative importance of CCS cost versus the GHG price. When the GHG price is low, higher CCS costs are more significant relative to the cost of emitting GHG; therefore, the quantity of CCS is more sensitive to the cost. When the GHG price is high, the CCS cost is less significant compared to the cost of emitting GHG, reducing sensitivity to the cost of CCS.

Combined Effect and Management Implications

The model is not highly sensitive to either of the parameters that I tested, but combined they produce a significant variation in the BAU and policy forecasts. Across the entire range of parameters I tested, the difference in BAU emissions forecasts is 0.72 GtCO$_2$e and the difference in the policy emissions forecasts (at 300 $/tCO$_2$e) is 0.36 GtCO$_2$e in 2050 (Figure 14, p.52). This difference results in a large change to the GHG price needed to achieve the 50% reduction below year 2000 emissions by 2050. At the low range, 2.2 Gt must be reduced from the 2050 BAU to achieve this goal, requiring a

GHG price of 200 $/tCO$_2$e in 2050. At the high end of the range, emissions must fall 2.9 Gt below BAU emissions, requiring a carbon price slightly over 300 $/tCO$_2$e (Figure 17). Additionally, the total abatement cost will be very different. Although the low industrial growth and low CCS cost MAC curve is steeper, this is because the BAU forecast has fewer emissions. The total abatement cost, bounded by the area under the curve to the required emissions reduction (vertical line at 2.2) is much smaller than the total abatement cost of the high growth/high CCS cost scenario (area under that curve to the vertical line at 2.9).

Figure 17: Marginal abatement cost under different industrial growth rates and CCS costs



Ind. growth refers to the rate at which the industrial sector output is growing relative to GDP. The curves represent the two extremes of my sensitivity analysis.

If the GHG price needed to achieve the policy target varies by 100 $/tCO$_2$e how robust is the model's response to a carbon tax? First of all, it is important to stress that while the GHG price changes by one third of the value under the initial assumptions, the individual cost and growth parameters change by a factor of three and four respectively. This keeps the change in GHG price in perspective since it is still insensitive to smaller changes. Furthermore, regardless of which scenario is most accurate, a large GHG price is needed to reduce emissions below the target level by 2050 and this price can rise gradually over the model run. This is independent of the total abatement cost or the abatement options that are used. As well, the CCS cost and rate industrial growth will become less uncertain over time. GHG prices can be changed in response to new information and updated model outputs. Thus the policy action that I recommended, a tax that increases linearly from 2011 to reach 300 $ in 2050, is reasonably robust so long as it can be raised slightly if CCS proves to be more expensive, or lowered if industrial growth is slower than I assumed.

CHAPTER 5: DISCUSSION

In the last chapter, I presented the simulation results of CIMS-TE. I compared energy consumption and GHG emissions of the BAU and policy forecasts, noting that a GHG price rising to 300 \$/tCO_2e in 2050 will result in emissions falling by 50% below 2000 levels. I also presented the cost of reducing GHG emissions in the TE, highlighting the importance of low-cost mitigation in the electricity sector and the large potential for mitigation in the industrial manufacturing sector. The results demonstrate how fuel switching to electricity and the use of carbon capture and storage are important mitigation options. Finally, I explored how changing the rate of industrial growth and the cost of carbon capture and storage (CCS) changed the GHG price needed to achieve the policy target I set earlier in this report.

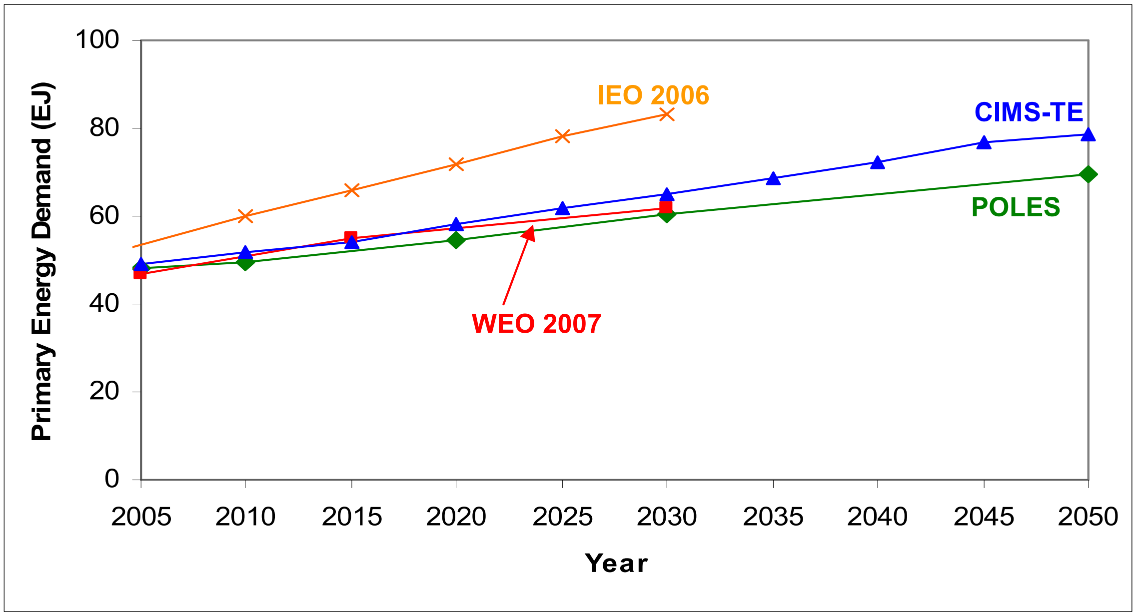
In this chapter, I expand my discussion of these results. First, I compare my BAU forecast with the baselines other modellers have developed. This comparison helps fulfil my first research objective, which is to develop a plausible BAU forecast that can support or challenge the modelling structures previously applied to the TE. Second, I compare the MAC curves of CIMS-TE with the MAC curves of other CIMS models to understand how the cost of reducing GHG may vary among regions. I then compare the abatement cost forecast in the TE produced by SGM, POLES, MIT EPPA and CIMS-TE to understand how differences in modelling structure can result in different abatement costs. Finally, I discuss the strengths and limitations of the current CIMS-TE model and explain future work to be done with the model

Comparison of BAU with other studies

Although some of the sector output forecasts in CIMS-TE are based on the POLES model (EC, 2006) and the International Energy Outlook (IEO) energy supply forecasts (EIA, 2007b), I made no effort to calibrate the GHG and energy consumption forecasts of my model to existing forecasts. One of the purposes of making CIMS-TE was to compare how a model structure that had not yet been applied to the TE would compare with the forecasts of other models. This comparison allows me to challenge or support other model structures and adjusting my model to match existing outputs would have eliminated this possibility.

The BAU primary energy demand forecast that CIMS-TE produced supports the projections made by the POLES model and the World Energy Outlook (WEO) (Figure 18). After 2030, POLES and CIMS-TE diverge in their forecasts by 10 EJ, or about 13%. This difference is mainly due to divergent assumptions about the rate of growth in the industrial sector. The IEO forecast, on the other hand, takes a different trajectory from the other forecasts that I have presented. Higher forecasted rates of economic growth and sector outputs appear to be the cause of this rapid rise in energy consumption. The IEO 2006 uses an annual average GDP growth of 4.4% from 2005 to 2030 versus the 3.1% in CIMS-TE and POLES.

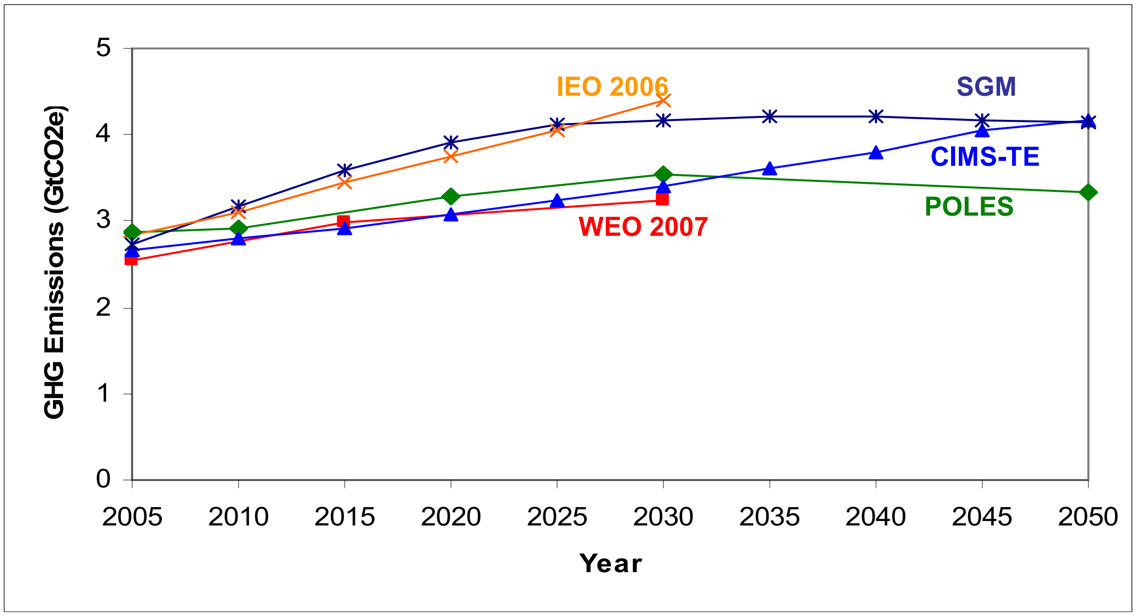
Figure 18: BAU forecasts of primary energy demand in the TE



WEO is the World Energy Outlook produced by the IEA (IEA, 2006b). The POLES forecast is for a region that does not correspond exactly to the TE (EC, 2006), so the values I present here have been scaled by the ratio of population between the two regions. IEO is the International Energy Outlook produced by the EIA (EIA, 2007b).

The larger forecast of energy consumption in the IEO 2006 translates into a larger GHG emissions forecast (Figure 19). The SGM model also forecasts a rapid mid-term rise in GHG emissions, although this stabilizes after 2030. The SGM is a computable general equilibrium model that tracks the labour market among other things. Because of the slowly declining population forecast in the TE, the SGM model indicates that there will be an economic slow-down and a reduced rate of GHG emissions due to limited labour. Again, the forecast of emissions from the WEO and POLES closely match the CIMS-TE forecast to 2030. Before this time, the POLES emissions are slightly higher because it forecasts less development of hydroelectric power. As such, the POLES electricity sector uses more coal and natural gas and emissions are somewhat higher than CIMS-TE. After 2030, the POLES emissions drop because the BAU includes a modest carbon price from the European Union.

Figure 19: BAU forecasts of GHG emissions in the TE



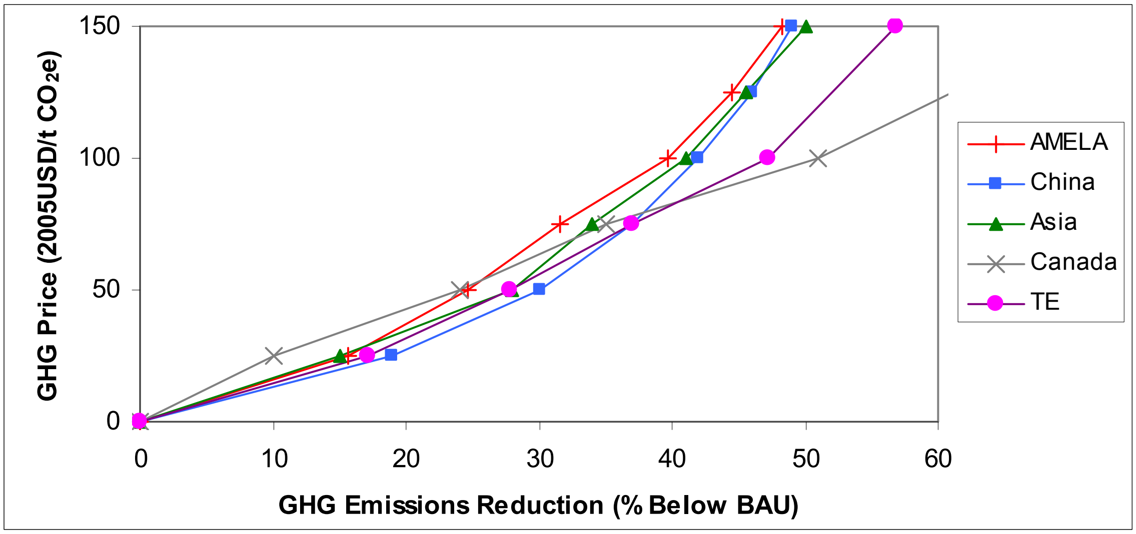
The SGM model is the second generation model (Sands, 2004)

MAC Curve Comparisons

Ultimately, the intentions of energy modelling go beyond comparisons of forecasts and assumptions and should feed into policy development and analysis. The cost and environmental effect of a policy are crucial to this analysis and can be studied using MAC curves. Comparisons of MAC curves can show where abatement will be least costly and which regions will benefit relative to each other due to a policy. They can also indicate the direction that emissions permits will flow if an international market is created and can illustrate how technology costs and availability in specific regions can affect the abatement cost. However, to make these comparisons, the MAC curves must be produced using the same baseline conditions, otherwise the differences in abatement cost could be more indicative of differences in the modelling approach. Therefore, the comparisons I make to other CIMS-Global regions highlight regional differences in abatement costs, while the comparison I make to other models of the TE emphasize the effect of different model structures and BAU assumptions on abatement cost.

In my analysis, I use a MAC curve that shows abatement as a percent of the BAU emissions in 2050. I do not show absolute emissions below the BAU because the regions I am comparing have large differences in their emissions. For example, CIMS forecasts that China will emit 12 times more GHG in 2050 than Canada. Consequently, the Canadian curve appears steeper than the Chinese curve and abatement appears more costly in Canada. This is simply because Canada cannot mitigate more GHG than it actually emits, thus an absolute MAC curve gives very little information other than a comparison of the quantity of GHG emitted by various regions. Furthermore, because some targets propose reducing emissions proportionally from a given year, a relative MAC curve is more useful

Figure 20: Comparison of CIMS MAC curves



AMELA is Africa, the Middle-East, and Latin America (Melton, 2008). Asia is developing Asia excluding China (Goggins, 2008). CIMS China and Canada taken from (Bataille et al., 2008). The MAC curves are based on constant GHG emissions prices from 2015 to 2050 in 2005 US dollars.

At GHG prices less than 50 \$/tCO_2e, the TE curve indicates that abatement costs are slightly lower than other regions, especially Canada, although they are higher than China. China may benefit from a large amount of coal in the BAU that can be cheaply switched to natural gas (Tu, 2004). In the TE, many processes already use natural gas and fewer inexpensive fuel switching opportunities exist. The low cost abatement in the TE is from the electricity sector where nuclear power and hydroelectricity are readily available (see Figure 12, p.51) At higher GHG prices, the TE MAC curve shows more abatement is possible in the study area than in other regions except Canada, likely due to the unconstrained quantity of CCS that is available. Canada appears to have more abatement at higher prices, perhaps using CCS with enhanced oil recovery.

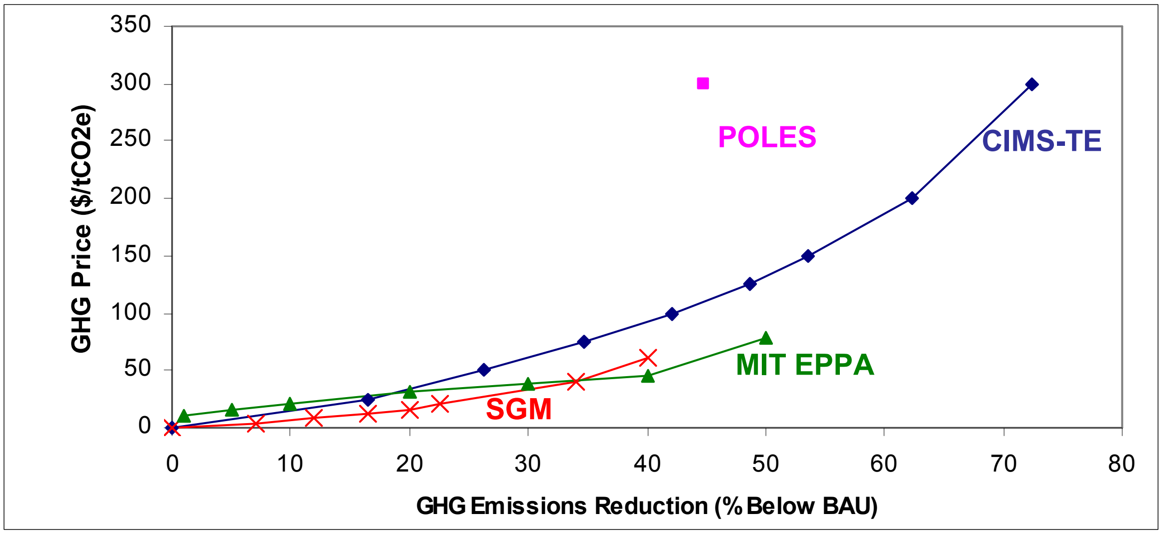
The general impression from Figure 20 is that Canada and the TE have lower abatement costs for mitigation greater than 40% of the BAU. Additionally, it also appears that the MACs of the regions in question are very similar until higher GHG prices are applied. The first impression, that the TE has a lower relative MAC is often seen in other studies of abatement costs. The low-cost Canadian abatement and the general similarity of the curves is not supported by other research, which indicates a wider divergence in the relative MAC curves of global regions, even at lower GHG prices (den Elzen et al., 2005; Ellerman and Decaux, 1999; Morris et al., 2008; Sands, 2004).

The fact that CIMS global is essentially a Canadian model modified for other regions may explain the similarity in MAC curves in this study. It is possible that by 2050 the technologies and processes in the models converge unless significant regional differences are included, such as limits on hydroelectricity, nuclear power, and CCS. Therefore, the cost of abatement appears similar 45 years in the future. The MAC is lower in the TE perhaps only because of the conditions I listed above. However, under the assumption of an increasingly globalized economy, technological convergence around the world by mid-century may be a reasonable assumption. Future research should examine the validity of these results and should investigate short and mid-term abatement costs to see if the regional differences are more pronounced.

The technologies available in the model may also explain the divergence of the Canadian MAC curve at higher GHG prices. While the CIMS-Global models and the CIMS-China models are based on an older technology data set, the Canadian model has been recently updated to include more technological options to reduce emissions. Therefore, the Canadian model will be more responsive to higher GHG prices and will have a shallower MAC curve.

Discrepancies with previous cost forecasts are also evident when comparing to other studies of the TE (Figure 21). However, the MACs are consistent at lower GHG prices. The TE roughly corresponds to the former Soviet Union (FSU) region used by the models in Figure 21. Therefore, CIMS-TE forecasts MACs that are higher than the SGM and MIT EPPA forecasts. Since both these models use a top-down methodology with limited technological detail, the expectation was for higher-cost abatement due to a lack of technological abatement. There are several reasons why this outcome did not happen. In top-down models, the MACs depend on the elasticities of substitution that determine how the labour and capital substitute for energy and emissions. If this substitution is relatively elastic, then the MACs will be lower.

Figure 21: Marginal abatement cost forecasts in the TE



Source: (EC, 2006; Morris et al., 2008; Sands, 2004). The SGM and MIT EPPA curve cover the former Soviet Union. The SGM curve assumes a constant carbon price from 2005 onward, while the CIMS, MIT EPPA, and POLES data assumes a rising carbon price. Prices are in 2005 US dollars.

Furthermore, top-down models often have 'backstop' technologies that become economically viable at certain GHG prices and can reduce the MACs. For example, at 200 $/tCO$_2$e, wind power used with biomass thermal plants might become a competitive technology in the electricity sector. Consequently, the cost of electricity would stabilize at that GHG price, consumers would electrify their technologies and the MAC curve would flatten until all reasonable electrification opportunities were exhausted. These 'backstop' technologies exist in CIMS as well, but behavioural realism tempers their penetration into the market. The heterogeneity parameter in particular ensures that no technology suddenly captures all the new stock in the market. Rather, consumers adopt technologies incrementally, within a heterogeneous market, consistent with their preference to maintain the quality of their energy services while avoiding large upfront costs and unfamiliar technologies. Consequently, the MAC curves CIMS produces tend to rise consistently.

Although CIMS may provide a more accurate model of technological change, SGM and MIT EPPA can endogenously model structural change and equilibrium energy production under global GHG mitigation policy. In CIMS-TE, assumed elasticities determine how industrial and energy output change as the cost of production changes under a GHG price. In SGM and MIT EPPA, the outputs are balanced against global demand and they respond to changes in demand induced by policy. Investments in the industry and energy supply can move to other sectors, changing the structure of the economy while reducing the GHG emissions per unit of GDP generated. It is possible that CIMS underestimates both the changes in output and the changes in structure, resulting in more emissions at a given GHG price and a steeper MAC curve.

Finally, since CIMS-TE is based on a Canadian technology database, the baseline energy intensity might be too low. This would eliminate some of the low-cost mitigation opportunities and show high MACs for lower proportional abatement.

Based on the single data point from the POLES model, it appears that CIMS-TE forecasts lower cost abatement for the TE. The inclusion of a small carbon tax in the POLES BAU is one likely cause of this difference. Since the low cost abatement options already happen in the POLES BAU forecast, the abatement in the policy forecast will be higher cost. As well, CIMS-TE has more technological detail than POLES and may be exhibiting a greater ability to change as zero-emissions technologies are adopted, producing lower MACs.

Unfortunately, this analysis is a comparison of models with different assumptions about the future of the study area, so the insights based on these cost differences are exploratory at best. To make a conclusive comparison of how model structure affects the MAC curve for the TE, future researchers need to use these models together applying the same BAU assumptions.

Strengths, Limitations, and Future Work

The value of CIMS-TE is that its forecasts of MACs and abatement actions are derived using real technological data and an empirically derived representation of decision making. The TE have not yet been studied using this modelling framework. Therefore, the results CIMS-TE has produced are novel and, given that the model is calibrated by sector and fuel to high-quality data, potentially useful. Unfortunately, the Canadian technology database and the possibility that the model is misrepresenting the macro-economic effects of climate policy limit the credibility of these results.

Nonetheless, the data within the model is the same that is available to other global modellers. One could argue that the real technological parameters and realistic behaviour parameters, all based on extensive data collection and research, actually increase the data quality in CIMS. Furthermore, a credible representation of macro-economic effects in CIMS-TE only requires the input of credible parameters describing changes in sector output and energy trade in response to policy. Still, the MAC curve of CIMS-TE is suspiciously similar to the other CIMS regions and is not consistent with other comparisons of abatement costs for the study area. This observation needs to be explained. Further refinement of CIMS-TE can help show whether this result is valid and will expand the understanding of how models affect the abatement cost forecasts.

The first set of recommended improvements, attempting to verify base year energy intensities and pairing CIMS-TE with a full-equilibrium model, should be considered for any subsequent work with the model. These projects are likely to require small changes to the model itself and have more of a research focus. Hence, they could be considered ways to use the model rather than ways to continue building it. The second set of recommended improvements are long-term ideas that may become priorities given the right research demands. These include the addition of a heat supply sector, continued sensitivity analysis, improved forecasts of unconventional oil production, and greater regional disaggregation.

As with any model, the sector output forecasts and energy price forecasts can be updated as information becomes available in order to maintain a plausible BAU. In the case of the TE, this includes monitoring the region's progression or regression from a market economy. CIMS-TE runs on the assumption that firms and consumers will decide how to provide themselves with energy services. The algorithm that models these decisions is based on the assumption of a market economy where the actors maximize their welfare. The energy price forecasts in CIMS-TE are also based on the assumption that fuels will trend towards market pricing.

Short-Term Follow-up Work

Confirmation of Base Year Energy Intensities

The major assumptions and sector forecasts in CIMS-TE are based on the best available information and permit a reasonable projection of the BAU and policy forecasts. Furthermore, calibration against IEA data allows each sector to begin the simulation consuming an accurate amount of energy and emitting an accurate quantity of GHGs. Despite this, the base year energy intensities, the amount of energy consumed per unit service delivered, are largely unknown at the technology level in all sectors except for transportation. Generally, the least energy efficient technologies in the Canadian database determine the energy intensities. This means the possible improvements in energy efficiency and the GHGs that can be reduced by this abatement action are also largely unknown. This data gap may in part explain why the TE MAC curves produced by CIMS are different from other curves for the study region, especially given the age of the capital stocks in the TE that, under the right incentive, could allow a rapid turnover of technology.

To resolve this issue, the first improvement to this model could involve a study of the energy intensities of a few key technology nodes. These nodes are residential and commercial shells, natural gas pipeline transportation, natural gas fuelled electricity stations, industrial boilers, cogenerators, and kilns. As well, the aggregate energy intensities of the sectors whose outputs are based only on energy consumption could confirm that CIMS-TE uses the right sector output. These sectors are commercial, residential, and other manufacturing. Verifying the energy intensities in CIMS-TE would vastly improve the credibility of the results, making the forecasted technological change in response to climate policy more accurate.

Maintaining and updating a CIMS model as I have described is a labour intensive process, but I feel that these improvements could be made while using the model to research climate policy in the TE. This is especially true if it were done in collaboration with experts on the energy-economy system of the TE who are interested in this avenue of research. The value of CIMS-Canada comes from the of improvements that have been made over several years during its use for a wide variety of applications. We do not have the knowledge or time to improve CIMS-TE in the same way, so it is critical to network with those that do. Cooperating with others who study the TE would provide the interactions with clients, researchers, industry representatives and other modellers that allow continuous improvement of the model. While the current version of the model may not be a perfect policy analysis tool, it provides a framework to direct the research that will improve it while it is used.

Improved Macro- economic Realism

Although CIMS-TE is limited by uncertainties in the parameters, a deficiency in the representation of the macro-economic effects of climate policy is perhaps a greater inadequacy. Even if the forecasted effect of a group of policies are inaccurate due to inaccurate technology parameters, the model may still give a reasonable projection of the performance of these policies relative to one another. However, an incorrect representation of key relationships in the model structure could significantly reduce the value of the model for policy analysis by giving a false interpretation of the relationships and dynamics within the system. To produce more reliable forecasts, the model must describe changes in sector output and energy trade in response to policy. In CIMS-TE, the elasticities that govern these relationships are taken from the Canadian model, but these elasticities could, in future, be taken from a model that excels in its macro-economic realism and also models the study area.

The results of the TE policy forecast reaffirm the importance of incorporating trade. Under the 300 \$/tCO$_2$e GHG price, 15% of the avoided emissions in 2050 are due to output changes. How would output change if we assumed that supply and demand for goods and energy were balanced globally? Over 60% of the lost output occurs in two subsectors, cement production and natural gas extraction. If less cement is produced in the TE, would the demand for cement disappear or would the cement be imported from elsewhere? If the country of origin did not have similar GHG reduction policies, then this trade flow would cause carbon leakage, where emissions avoided by output reductions simply happen in another country. On the other hand, the TE has large volumes of natural gas and a lot CCS potential. If a global GHG mitigation policy were in effect, then the TE could increase its cement production while taking advantage of its low carbon fuel source and CCS capacity.

The natural gas subsector could be similarly affect by greater macro-economic realism. The current policy forecast indicates a large drop in natural gas output in response to a GHG price. However, most of the extracted gas is destined for export. Since natural gas has a low carbon content, relative to coal and oil, world demand for this fuel could rise in response to a global climate policy. Higher natural gas prices might encourage more production even under a high GHG price and the output from the sector would not drop as severely.

The elasticities that determine the macro-economic response to climate policy can be informed by a model that excels in the representation of this aspect of the energy-economy system. These models are typically computable general equilibrium models that require estimates of how capital can be substituted for energy throughout within the economy. In this respect, CIMS-TE is the better model and could inform this substitution, thereby improving the accuracy of the macro-economic parameters that will feed into CIMS. These parameters could be developed for a series of scenarios that describe global GHG mitigation agreements. The extent to which the TE will change its energy exports or change its consumption of domestically produced energy intensive goods will depend on which regions are reducing their emissions. Thus, under a variety of assumed policy futures, CIMS-TE could incorporate a more plausible representation of the macro-economy.

Long-term Projects With CIMS-TE

Addition of a Heat Supply Sector

A further improvement to the model structure would be the addition of a heat supply sector. In CIMS Canada, heat is only produced and used within industrial facilities and there is no distribution network. In the TE, heat is produced in public and private plants, as well as within industrial facilities and it accounts for over 30% of final energy consumption in Russia and 10-11% elsewhere (IEA, 2004a). Heat is purchased by all sectors for process heat and for space heating using district-heat distribution networks.

Although all sectors use district heat, I have only included it in the residential sector, this being the most different sector from the Canadian model. However, a model of the TE without a specific heat sector is similar to modelling electricity production within each subsector rather than with a single electricity supply sector. The energy-efficiency and cost effectiveness that is gained by using large scale heat production facilities is not captured by CIMS-TE, thus limiting abatement options. In an accurate model, there would be fewer smaller boilers, more sale of waste heat from industry to households and between industries, and more zero emissions heat generation options including nuclear power and geothermal energy. Additionally, there would be more large scale and lower cost opportunities for CCS used with heat production. CCS is cheaper per unit carbon avoided with larger facilities. Using the existing heat distribution system rather building a new CO_2 collection network would further reduce costs.

Adding a heat sector to CIMS-TE would improve its accuracy and utility as a policy analysis tool and it would also have useful applications outside of this project. The transfer of waste heat between sectors is an abatement opportunity that is possible in regions outside of the TE. CIMS will require an integration of heat supply and demand to capture this significant energy-efficiency opportunity, and a heat supply sector would be necessary to do this. Just as electricity demand from the current sector model can be reduced by the use of cogenerators, the heat demanded from a heat supply sector could be reduce by allowing the use of waste heat for less energy intensive industrial process and space heating.

Continued Uncertainty Analysis

Sensitivity analysis should continue as a means to define what parts of the model require the most attention. Assumptions about the rate of industrial growth and the cost of CCS clearly affect the forecasted emissions, although they have a dampened effect on the GHG price necessary to reach a policy goal. Although sensitivity to behavioural parameters has been tested by Tu (2004) and Melton (2008), it would be worthwhile to test them in CIMS-TE as well. Two further assumptions that need this type of analysis are the quantity of nuclear energy and hydroelectricity that can exist in the TE. These two technologies appear fundamental to the provision of the large quantities of zero emissions electricity that is consumed in the model, and are significant to the policy forecast. Once important parameters are identified, they could have probabilities attached to their range of values. Based on the model's sensitivity to these parameters, researchers could then apply a quantitative measure to their confidence in the model's outputs.

Improved Forecasts of Unconventional Oil Production

An estimate of unconventional oil production during the model run is needed. While there are no current forecasts for this production, conventional oil reserves based in the TE are likely to be significantly depleted by 2050. Estimates of recoverable unconventional oil increase the reserve by another 46 billion barrels, so it is possible that this oil will be exploited during the simulation period. Unconventional oil production is four to five times more GHG emissions intensive that conventional oil production. Assuming the same amount of oil is produced, emissions in the TE could increase by 5-15% (200-600 Mt) in 2050, significantly altering the MAC and the abatement actions in use.

Greater Geographical Disaggregation

A final improvement to the model could involve further disaggregation of the study region. Because of the coarse geographic aggregation of CIMS-TE, the policies that can be tested and the applicability of the results are limited. The model outputs are an average that may not accurately represent any specific location in the study area. Modelling a large region has advantages during the model development phase, making it a less data-intensive and faster process. However, this must be balanced against usability. Many parameters in the model are represented as an aggregate input. For example, energy prices in Russia tend to be half the price as elsewhere in the TE and a weighted average price is incorrect for the entire study area. Growth of the economy and structural change are also crudely represented in a larger region. Currently, the model uses the assumption that the energy path all the countries in the TE will follow will be identical, whereas some regions may see more intense industrialization, population growth, and energy demand than others. As well, the large region limits the resolution at which policy can be analysed. Only policy architectures that treat all the countries of the TE equally can be tested, but it is possible that some countries would not have the same policy targets as others. The standard of living and level of development is not even across the TE, thus it is possible that some countries would enact less strict policies in favour of greater economic development.

To address these problems, Russia could be modelled separately. The remaining portion of the study area emits a small fraction of global GHG emissions and effective research in global policy architectures can be conducted while treating it as a homogenous unit. Russia on the other hand accounts for roughly half of all emissions and energy use in the study region and its participation in international agreements will be important in mitigating the risk of climate change. Thus, a model of Russia specifically could be valuable and should be considered for future CIMS-Global work.

CHAPTER 6: CONCLUSION

Justification for this Research

The risk of climate change is increasing as the quantity of GHGs emitted by humans rises. To reduce the risk, we must significantly reduce global GHG emissions but this requires an international effort employing policies that are effective, efficient, equitable, and politically acceptable. Only well designed policies will succeed. Energy-economy models are critical to the development of these policies.

Due to the complexity of the global energy system, energy-economy modellers have used many simplifying assumptions when attempting to design the ideal model for GHG policy analysis. The resulting models tend to forecast a wide range of mitigation costs and potentials. Hybrid energy-economic models, such as CIMS, attempt to close this methodological gap and provide results that are more useful to policy makers. However even hybrid models can take many forms. No single model has perfected its representation of the three elements that would make it most useful for GHG policy analysis: behavioural realism, technological explicitness, and macro-economic relationships

The CIMS model improves the representation of these three aspects, but it is not currently a global model. While other global hybrid models exist, CIMS global would be unique because of its high level of technological detail in all energy-consuming sectors, with over 2500 unique technologies competing in a simulation framework to provide energy services. Of equal importance, CIMS uses empirically derived parameters to represent the behaviour of firms and households at the micro-economic level, while balancing the supply and demand of energy and representing output and demand changes in response to cost changes at the macro-economic level. Therefore, CIMS-Global would be a novel and potentially valuable tool for the analysis of global policy architectures.

Research Objectives and Major Findings

In this study, I have presented the development and analysis of the transition economies (TE) region of CIMS global. I pursued five major research objectives:

1. Develop a CIMS model that can forecast plausible "Business as Usual" (BAU) energy use and GHG emissions in the TE to 2050. Study this forecast in the context of previous model output for the study area.

The BAU scenario that I developed forecasts emissions rising from 2.6 GtCO$_2$e in 2005 to 4.2 GtCO$_2$e by 2050. Energy consumption increases by 75% over this period to 78 EJ in 2050. Rapid growth in the industrial sector and the energy supply sector drive this trend. The CIMS-TE BAU forecast matches that of the POLES model and the World Energy Outlook to 2030. To 2050, POLES forecasts lower emissions but a similar energy consumption as CIMS-TE. The IEO forecasts much faster growth in energy consumption and emissions to 2030. The SGM also predicts a rapid rise in GHG emissions to 2030, but by 2050 it forecasts annual emissions similar to CIMS-TE.

2. Examine carbon price-path that results in a 50% regional reduction of GHG emissions from the year 2000 by 2050 and compare that to the path that would achieve a 50% global reduction from the same baseline but under the contraction and convergence policy architecture

Based on the assumptions of economic growth I have used, the model forecasts that a GHG price starting in 2011 and rising linearly to 300 \$/tCO$_2$e by 2050 will achieve the first policy target and emissions in 2050 will be 1.16 GtCO$_2$e. The model indicates that the second policy target cannot be met through domestic mitigation alone without the application of extreme GHG prices. At the GHG prices required to achieve this abatement, the uncertainty introduced in the model is too high to make the outputs useful for analysis. Behaviour and technology are likely to change beyond the dynamic range of the model in response to such a large price signal.

3. Study the methods by which emissions are reduced in response to that price-path

In response to the GHG price that reaches 300 \$/tCO$_2$e in 2050, approximately 3 GtCO$_2$e per year are avoided. Carbon capture and storage (CCS) prevented 30% of these emissions, fuel switching to electricity, hydropower and nuclear prevented 26%, and output changes, energy efficiency and other GHG controls were responsible for the rest.

4. Examine and compare cost of emissions reduction in my region with other studies of the TE and with other regions already included within CIMS

Using MAC curves, I verified that the cost of abatement falls if the abatement occurs over longer times in the TE, consistent with results from other regions. More adjustment time allows the natural turnover of capital stock to build up low emissions technologies without the cost of early retirement and with the benefit of economies-of-scale and learning for new technologies. CIMS-TE marginal abatement costs are very similar to other CIMS regions, except more abatement relative to the BAU occurs in the TE at higher prices, possibly due to a large capacity for CCS, nuclear power and hydroelectricity that supply low-cost and low-emissions electricity. CIMS-TE forecasts higher cost GHG abatement than does the SGM and the MIT EPPA model. Divergent representation of technological change and the equilibrium of global supply and demand may cause this result. On the other hand, CIMS-TE forecasts costs that are less than the POLES model forecasts. The GHG price in the POLES BAU forecast may explain why the POLES abatement costs are higher for the same relative reduction in emissions.

5. Examine the sensitivity of the GHG emissions and abatement costs to key parameters

I examined the sensitivity of the GHG price that achieves the policy target to changes in the rate of industrial growth and the cost of CCS. Over the range of values I tested, BAU and policy emissions changed greatly. With over a threefold change in the cost of CCS and a fourfold change in the rate of industrial growth, the GHG price needed to achieve the 50% reduction below year 2000 emissions varied from 200 to 300 \$/tCO$_2$e. While this range is large, the GHG price is not very sensitive to smaller changes or changes in a single variable. This is especially true for the CCS cost as other abatement options are available at a slightly higher marginal cost. Regardless of the values I used in the analysis, the model demonstrates that a rapidly rising GHG price starting in 2011 could significantly reduce emissions; however, it would need to be raised or lowered depending on future industrial growth and future CCS costs in the study area.

Future Work

Future researchers may improve the structure and data of CIMS-TE, continue to update sector output and energy price forecasts, as well as review key parameters.

Likewise, they should continue to do sensitivity analysis with the model, integrate energy and material trade among the CIMS-Global regions, and consider whether a model specific to Russia might make CIMS more useful for policy analysis.

Additional work with CIMS-TE should aim to produce

- A confirmation of base year energy intensities by sector (energy use per unit output).
- An update of parameters describing macro-economic response to climate policy, informed by a model that excels in the aspect of energy-economy modelling

If data and time permit, specific refinements should include:

- An addition of a heat supply sector and distribution system.
- A confirmation of hydroelectric and nuclear energy potentials as well as a sensitivity analysis of these parameters.
- An update of energy prices and the assumption of a transition to a free market economy.
- An investigation of unconventional oil production.

Finally, these improvements to CIMS-TE will be labour intensive. To see them through, other researchers with an interest in modelling the region should be able to access the model and use their expertise to continue its development. The value of the CIMS-Canada model has grown over several years by using the model and exposing it to outside input. If CIMS-TE is to be maintained, updated, and improved, it too will need to be used regularly by experts in the field.

APPENDICES

Appendix A: Regional Definition

CIMS-TE includes the nations of the former Soviet Union and non-OECD Europe. The regional boundaries of this analysis are defined according to the classification used by International Energy Agency (IEA) when creating their regional energy balances (IEA Statistics, 2003a). The following nations are in the TE:

Albania, Armenia, Azerbaijan, Belarus, Bosnia-Herzegovina, Bulgaria, Croatia, Estonia, Serbia and Montenegro, the former Yugoslav Republic of Macedonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Romania, Russia, Slovenia, Tajikistan, Turkmenistan, Ukraine and Uzbekistan. This region also includes Cyprus, Gibraltar and Malta.

Appendix B: Calibration Results

After calibration, the total energy consumption of CIMS-TE in 2005 was 0.2% higher than the consumption in the IEA balances. The energy consumption of residential, commercial, industry, and transportation sectors were also within 2% of the historical data. The electricity sector used 7% more energy than the data indicated, while the energy transformation used 9% less energy than indicated by the data (Table 8). In both cases, the sector outputs are set with reliable data and the difference in energy consumption is due to technology choices being made during simulation. Changing this result would require time consuming alteration of parameters governing the allocation of the market share in the simulation. Given that the total energy consumption of the region closely matches the data, I did not attempt to perfectly calibrate each sector. The classification of ‘Other’ fuels by CIMS versus the classification by the IEA may explain a portion of the difference in the consumption of refined petroleum products (RPP). For example, petroleum coke and pitch are counted under other fuels by CIMS, whereas it may be RPP according to the IEA. Industrial applications typically consume these fuels and the largest difference in RPP consumption is in the industry sector and the energy supply sector, supporting this possibility.

Table 8: Energy consumption calibration results (EJ)

IEA 2005	RPP[a]	Elec.	Gas	Coal	Other, renew	Nuclear	Hydro	Sector Total	
Transportation	4.2	0.2						4.4	
Commercial	0.2	0.7	1.0	0.1	0.05			2.0	
Industry	1.0	1.9	4.9	2.8				10.6	
Residential	0.8	1.0	6.1	0.8	0.4			8.9	
Electricity	0.4		4.0	3.1	0.05	3.0	1.1	11.6	
Energy Sup.	0.8	1.1	3.3	0.1	0.05			5.3	
Fuel Total [b]	7.3	4.9	19.3	6.8	0.5	3.0	1.1	**42.9**	
CIMS-TE 2005	**RPP[a]**	**Elec.**	**Gas**	**Coal**	**Other, renew**	**Nuclear**	**Hydro[c]**	**Sector Total**	**% diff.**
Transportation	4.3	0.1						4.4	-0.1%
Commercial	0.2	0.8	1.1					2.1	1.9%
Industry	0.7	2.0	4.9	2.7	0.2			10.4	-1.8%
Residential	0.5	1.1	6.4	0.6	0.2			8.8	-1.1%
Electricity	0.4		4.4	3.4	0.1	3.1	1.2	12.4	6.8%
Energy Sup.	0.4	0.7	3.3		0.3			4.8	-8.7%
Fuel Total [b]	6.5	4.7	20.0	6.7	0.8	3.1	1.2	**43.0**	
CIMS-IEA	-0.8	-0.2	0.8	-0. 1	0.3	0.1	0.06	**0.1**	
% difference	-11%	-3%	4%	-1%	50%	2%	5%	**0.2%**	

[a] RPP are refined petroleum products

[b] Totals may not add up due to rounding

[c] Corrected to match the IEA measurement based on amount of electricity generated rather than the potential energy of the stored water

Energy Supply and Transportation

Consumption is listed under the ‘own use’ in the IEA energy balance, but this does not include energy for pipeline transport which is included in the transportation sector. In CIMS-TE, pipeline transportation is included in the energy supply sector, so I had to disaggregate this energy from the IEA transportation total and add it to the ‘own use’ total. I determined the total energy used by pipelines, roughly 1500 PJ of natural gas, by calculating the difference in energy consumption from the IEA transportation sector and the Sustainable Mobility Project Model that covers vehicles only. There could be some confounding with oil pipelines here, so they are probably included by proxy in the model. As well, the RPP from the agriculture and forestry row of the IEA balances was added to the transportation sector total since CIMS includes off-road energy consumption.

Industry

This sector covers industrial manufacturing, or the industrial sectors in CIMS-TE that are not already in the energy supply sector. It includes the energy from the 'coal transformation' row of the IEA balances because this energy is used to make coke within the iron and steel sector.

Commercial

This sector includes public services, such as consumption by outdoor lights and government buildings. While this consumption is likely to be small, it is not directly represented in the CIMS model. However, by calibrating my commercial sector to the IEA data, I am including this energy consumption by proxy through the technologies that are in CIMS-TE.

Electricity, Heat, and Residential

Combined heat and power (CHP) stations produce a large fraction of the electricity in the TE. I used the ratio of heat to electricity produced to determine the proportion of energy used by the CHP plants that I would include in the electricity sector totals, consistent with the IEA methodology. Heat and steam within the CIMS-TE subsectors account for the rest of the energy that CHP plants consume.

In addition to CHP plants, the TE region has an extensive heat sector, whereas in CIMS, all heat is auto-produced within each sector. In order to calibrate, I had to convert the amount of heat used by the sectors in the IEA balance to an amount of fuel used in boilers and cogenerators within the steam and heat processes of CIMS-TE. From the energy balance, I was able to calculate a conversion efficiency for heat production. Using this value and the fuel mix the IEA listed for heat production, I was able to convert the heat used to the amounts of fuel used if heat were auto-produced as it is in CIMS-TE, rather than drawn from a distribution system as it is in reality

The IEA account of hydro energy is also different from its accounting in CIMS. By the IEA numbers, there is a 1:1 ratio of hydro energy to electricity produced. Essentially, the IEA measures the energy based on the amount of electricity it could produce, while in CIMS the ratio is 3:1, indicating the ratio between the potential energy of the water and the electricity that it will produce via the available technology. Because of this difference, I had to divided the hydro energy listed in the CIMS outputs by three to compare it to the IEA data.

Appendix C: Data Sources and Energy Prices

Table 9: Sector data sources

Sector	Source
Residential and Commercial	(IEA, 2004a)
Transportation	(IEA/WBCSD, 2004)
Electricity	(IEA Statistics, 2003b)
Industry	(IEA, 2006a; IEA, 2007; International Iron and Steel Institute, 2007; United Nations, Dept. of Economic and Policy Analysis, Statistical Divison, 2003; USGS International Minerals Statistics and Information, 2007)
Energy Supply	(IEA Oil Market Division, 2007; IEA Statistics, 2003b; Reece, 2004; Veazy, 2006)
Energy Prices	(IEA, 2008)

Table 10: Energy prices

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Natural Gas										
electricity	0.95	1.88	2.64	4.14	4.80	5.57	6.45	7.48	8.00	8.00
res/comm	2.82	3.63	4.40	6.07	7.04	8.16	9.45	10.95	11.00	11.00
industry	1.48	2.00	3.00	4.14	4.80	5.57	6.45	7.48	8.00	8.00
Coal	1.03	1.30	1.80	2.10	2.37	2.37	2.37	2.37	2.37	2.37
Electricity										
res/comm	8.6	21.2	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5
industry	10.0	18.0	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2
Diesel										
Personal	21.3	22.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Freight	16.1	18.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Gasoline	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6

2005 Source (IEA, 2008).All prices are 2005 USD/GJ

Appendix D: Exogenous BAU Sector Output Forecasts

Table 11: Sector output forecasts

	Units	2005	2010	2020	2030	2040	2050
Energy Demand Sectors							
Residential	Thousand households	111500	117300	121200	123400	127300	131200
Commercial	Million m^2 floor space	921	1090	1543	1956	2338	2556
Transportation							
Personal	Billion passenger kilometres	2117	2320	2941	3511	4159	4879
Freight	Billion tonne kilometres	2259	2504	3196	3869	4768	5888
Manufacturing Industry							
Chemical Products	Million tonnes	90	104	139	177	211	231
Industrial Minerals	Million tonnes	135	156	210	266	318	347
Iron and Steel	Million tonnes	140	151	210	273	326	357
Metal Smelting	Million tonnes	11	12	15	18	22	27
Mineral Mining	Million tonnes	411	458	616	827	989	1182
Paper Manufacturing	Million tonnes	11	11	15	19	24	28
Energy Supply Sectors							
Electricity Generation	TWh	1600	1747	1909	2108	2388	2681
Petroleum Refining	Million m^3	349	352	368	395	455	531
Petroleum Crude Extraction	Million barrels per day	11.6	13.7	15.8	17.6	16.1	14.9
Natural Gas Extraction	Billion m^3	916	1163	1441	1756	1865	1974
Coal Mining	Million tonnes	554	512	470	457	563	669

Appendix E: Detailed BAU Energy and Emission Forecast

Table 12: BAU energy consumption forecast

	Energy Consumption (EJ)						*Average Annual Growth Rate (%)*	
	2005	**2010**	**2020**	**2030**	**2040**	**2050**	***2005-2030***	***2030-2050***
Total Primary Energy Consumption								
Oil	15	15.6	16.6	17.7	20.4	22.1	*0.6*	*1.7*
Natural Gas	20	22.7	26.8	29.8	29.1	28.6	*1.9*	*-0.4*
Coal	6.7	5.9	5.2	5.0	6.9	8.9	*-1.0*	*3.9*
Nuclear	3.0	3.2	4.4	6.1	7.9	9.1	*4.0*	*2.5*
Renewable	2.9	3.2	3.9	4.9	6.1	7.6	*2.8*	*2.7*
Other	0.8	0.8	1.2	1.6	2.3	2.7	*4.4*	*4.1*
Total	**48.4**	**51.4**	**58.1**	**65.1**	**72.1**	**79**	***1.3***	***1.1***
Electricity Generation Consumption								
RPP	0.4	0.3	0.2	0.1	0	0	*-3.0*	*-5.0*
Natural Gas	4.3	5.7	6.5	6.6	4.9	4.4	*2.1*	*-1.7*
Coal	3.4	2.8	1.7	0.9	2.4	4.2	*-2.9*	*18.0*
Nuclear	3.0	3.2	4.4	6.1	7.9	9.1	*4.0*	*2.5*
Renewable	2.9	3.2	3.9	4.9	6.1	7.6	*2.8*	*2.7*
Other/waste	0	0	0	0.2	0.5	1	*23.0*	*20.0*
Total	**14**	**15**	**16.7**	**18.8**	**21.8**	**26.3**	***1.3***	***2.0***
Residential and Commercial Consumption								
RPP	0.7	0.5	0.2	0.3	0.7	1.0	*-2.1*	*9.8*
Natural Gas	7.5	7.1	7.6	7.5	6.9	6.6	*0*	*-0.6*
Coal	0.6	0.4	0.1	0	0	0	*-3.8*	*0*
Electricity	1.9	2.2	2.2	2.2	2.5	2.9	*0.6*	*1.5*
other	0.2	0.2	0.1	0.1	0.1	0.1	*-2.0*	*0*
Total	**10.9**	**10.4**	**10.3**	**10.2**	**10.3**	**10.7**	***-0.3***	***0.3***
Energy Supply Consumption (including refinery feedstock and pipeline transport)								
Oil	15	15.6	16.6	17.7	20.4	22.1	*0.6*	*1.7*
RPP	0.4	0.5	0.4	0.4	0.5	0.6	*0*	*2*
Natural Gas	3.3	4.3	5.5	6.7	7.0	7.0	*4.1*	*0.2*
Electricity	0.7	0.8	0.8	0.8	0.8	0.9	*0.4*	*0.6*
Total	**19.8**	**21.5**	**23.8**	**26.3**	**29.5**	**31.6**	***1.3***	***1.0***
Industrial Consumption								
RPP	1.1	0.9	0.6	0.6	1.0	1.6	*-1.8*	*9.1*
Natural Gas	4.9	5.5	7.3	9.0	10.3	10.7	*3.4*	*0.9*
Coal	2.7	2.7	3.4	4.0	4.4	4.6	*1.9*	*0.7*
Electricity	2.0	2.2	2.8	3.4	4.0	4.6	*2.9*	*1.8*
Other	0.2	0.3	0.5	0.7	0.9	1.0	*10.0*	*2.0*
Total	**10.8**	**11.6**	**14.4**	**17.7**	**20.6**	**22.5**	***2.5***	***1.4***
Transportation Consumption								
RPP	4.3	4.8	6.0	6.9	8.2	10.0	*2.4*	*2.2*
Electricity	0.1	0.1	0.1	0.2	0.2	0.3	*1.5*	*2.6*
Other	0	0	0	0	0	0.1	*0*	*24*
Total	**4.4**	**4.9**	**6.1**	**7.1**	**8.4**	**10.4**	***2.4***	***2.3***

Table 13: BAU GHG emissions forecast

	GHG Emissions ($GtCO_2e$)						*Average Annual Growth Rate (%)*	
	2005	**2010**	**2020**	**2030**	**2040**	**2050**	***2005-2030***	***2030-2050***
Transportation	0.39	0.42	0.51	0.57	0.66	0.8	*1.9*	*2.1*
Residential/Commercial	0.53	0.48	0.45	0.45	0.46	0.47	*-0.6*	*0.3*
Electricity	0.54	0.55	0.48	0.42	0.46	0.54	*-0.9*	*1.4*
Industry	0.70	0.75	0.92	1.13	1.33	1.44	*2.5*	*1.4*
Energy Supply	0.50	0.61	0.73	0.86	0.90	0.94	*2.9*	*0.5*
Total	**2.7**	**2.8**	**3.1**	**3.4**	**3.8**	**4.2**	***1.1***	***1.1***

Appendix F: Detailed Policy Energy and Emission Forecast

Table 14: Policy energy consumption forecast ($300\$/\mathrm{tCO_2e}$ GHG price by 2050)

	Energy Consumption (EJ)						*Average Annual Growth Rate (%)*	
	2005	**2010**	**2020**	**2030**	**2040**	**2050**	***2005-2030***	***2030-2050***
Total Primary Energy Consumption								
Oil	14.9	15.4	14.8	14.2	14.4	13.5	*-0.2*	*-0.2*
Natural Gas	19.7	22.7	22.5	21.5	18.1	15.1	*0.4*	*-1.5*
Coal	6.4	5.6	4.0	3.1	3.9	4.2	*-2.1*	*1.8*
Nuclear	3.1	3.2	4.4	6.7	10.1	12.2	*4.6*	*4.1*
Renewable	2.9	3.2	4.3	6.9	10.1	12.7	*5.5*	*4.2*
Other/waste	0.8	0.9	1.2	2.2	3.9	5.7	*7.0*	*8.0*
Total	**47.8**	**51.0**	**51.2**	**54.6**	**60.5**	**63.4**	***0.6***	***0.8***
Electricity Generation Consumption								
RPP	0.4	0.3	0.2	0	0	0	*-4.0*	*-0.6*
Natural Gas	4.3	5.6	5.5	5.5	4.5	4.2	*1.1*	*-1.2*
Coal	3.4	2.8	1.5	0.4	0.6	0.9	*-3.6*	*8.2*
Nuclear	3.1	3.2	4.4	6.7	10.1	12.2	*4.6*	*4.1*
Renewable	2.9	3.2	4.3	6.9	10.1	12.7	*4.3*	*5.6*
Other/waste	0	0	.5	1.8	3.9	5.8	*218*	*10.9*
Total	14.1	15.0	16.1	20.5	28.4	35.9	*1.8*	*3.7*
Residential and Commercial Consumption								
RPP	0.7	0.5	0.2	0	0	0	*-3.7*	*0*
Natural Gas	7.3	7.3	6.7	5.2	3.1	1.2	*-1.1*	*-3.8*
Coal	0.6	0.4	0.1	0	0	0	*-4.0*	*0*
Electricity	1.8	2.0	1.8	2.3	3.4	4.4	*0.9*	*1.7*
other	0.2	0.2	0.1	0.1	0.1	0.1	*-1.1*	*0*
Total	10.6	10.4	8.9	7.6	6.7	5.8	*-1.1*	*-1.2*
Energy Supply Consumption (including refinery feedstock and pipeline transport)								
Oil	14.9	15.4	14.8	14.2	14.4	13.5	*-0.2*	*-0.2*
RPP	0.4	0.5	0.4	0.4	0.4	0.4	*-0.5*	*-0.1*
Natural Gas	3.3	4.3	4.4	4.5	3.7	2.8	*1.5*	*-1.9*
Electricity	0.7	0.8	0.9	1.2	1.2	1.4	*2.5*	*0.6*
Total	19.6	21.3	21	20.8	20.2	18.8	*0.2*	*-0.5*
Industrial Consumption								
RPP	1.1	0.9	0.5	0.4	0.6	0.7	*-2.5*	*3.5*
Natural Gas	4.9	5.5	5.9	6.3	6.9	6.8	*1.2*	*0.4*
Coal	2.4	2.4	2.3	2.8	3.2	3.3	*0.7*	*1.0*
Electricity	2.0	2.2	2.4	3.1	4.3	5.5	*2.2*	*3.9*
Other	0.2	0.3	0.2	0.2	0.7	1.2	*-0.4*	*21.8*
Total	10.5	11.3	11.3	12.8	15.7	17.6	*0.9*	*1.9*
Transportation Consumption								
RPP	4.1	4.6	4.7	4.5	4.4	4.4	*0.03*	*-0.1*
Electricity	0.1	0.1	0.2	0.3	0.6	1.0	*6.3*	*10.3*
Other	0	0	0	0.1	0.4	1.1	*0.6*	*46*
Total	4.3	4.7	4.9	4.9	5.4	6.4	*0.6*	*1.6*

Table 15: Policy GHG emissions forecast (300$/tCO$_2$e GHG price by 2050)

	GHG Emissions (GtCO$_2$e)						*Average Annual Growth Rate (%)*	
	2005	**2010**	**2020**	**2030**	**2040**	**2050**	***2005-2030***	***2030-2050***
Transportation	0.38	0.40	0.41	0.38	0.35	0.32	0.07	-0.76
Residential/Commercial	0.52	0.48	0.39	0.27	0.16	0.07	-1.89	-0.04
Electricity	0.53	0.53	0.35	0.16	0.07	0.03	-2.77	-0.04
Industry	0.67	0.72	0.60	0.54	0.48	0.41	-0.82	-0.01
Energy Supply	0.51	0.61	0.60	0.56	0.41	0.32	0.45	-0.02
Total	**2.60**	**2.74**	**2.35**	**1.92**	**1.47**	**1.16**	**-1.05**	**-0.02**

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