Cost-Effectiveness of Climate Change Policies for the United States

by

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Abstract

This research project applies a hybrid energy-economy model to compare the cost-effectiveness of different climate change mitigation policies for the United States. Five policies are compared: (1) a technology regulation phasing out coal and natural gas generation, (2) Clean Electricity Standard, (3) Corporate Average Fuel Economy Standard, (4) Vehicles Emissions Standard, (5) economy-wide GHG tax. The cost of these policies is estimated using three different methodologies. The first methodology is the techno-economic cost (TEC) measure, representing a 'bottom-up' or engineering costing methodology. The second methodology is the perceived private cost (PPC) measure, representing the 'top-down' or economist costing methodology. The third methodology uses the previous two methods to make a "best estimate" of welfare costs, called the expected resource cost.

Going by the expected resource cost measure, the study finds an economy-wide GHG tax is a quarter of the cost of two policy scenarios that implement tradable performance standards in the electricity and transportation sectors. For the electricity sector policies, the study finds that the clean electricity standard is 50% less costly than a technology regulation phasing out conventional coal and natural gas generation. For the transportation policies, the study finds that the Vehicle Emissions Standard is 15% less costly than the Corporate Average Fuel Economy Standard.

Keywords: Climate change policy; Energy-economy modeling; United States;

To generations past,
Grammy, Pappy, Baba, Papa

To generations present,
Luka, Olivia, Jaiden, Lina

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My first exposure to Dr. Mark Jaccard was reading an op-ed article that he wrote in the *Globe & Mail*. I remember being impressed about his knowledge of how to reduce pollution and how much it would actually cost society. Moreover, he actually seemed objective on these subjects, unlike most representatives from the business and environmental community. I had never heard of energy-economy modeling before, but if this was the method that gave Dr. Jaccard his knowledge, I wanted to learn it. Thankfully, Dr. Jaccard believes a political science student can learn modeling. I want to thank Dr. Jaccard for this opportunity. His dedication to the issue of climate change is truly inspiring.

Coming into this program, I hardly knew how to use Excel, let alone teach myself how to use modeling software and analyze results. Luckily, I was put on a project helping Suzanne Goldberg. Suzy is responsible for teaching me virtually all of my practical modeling skills. This project would not have been possible without her guidance and patience. Suzy also provided invaluable emotional support as I inevitably encountered frustrating moments in learning CIMS.

Whenever I experience anxiety about my career or educational choices, my Dad always says “just follow your nose, it will take you to where you are supposed to be”, and my Mom always says “don’t be such a ‘P’, just get down to it” (Myers-Briggs reference). For these small bits of wisdom and so much more, I am continually reminded of the greatness of my parents. I also want to thank my siblings for being amazing role models. My brothers are two of the most honest, genuine and hardworking people I have ever met. My sister has a heart of gold and a will of steel.

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AEO	Annual Energy Outlook
BAU	Business as Usual
CAFE	Corporate Average Fuel Economy
CCS	Carbon Capture and Storage
CES	Clean Electricity Standard
CIMS	Canadian Integrated Modeling System
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
EES	Ethanol Emissions Standard
EIA	Energy Information Administration
ERC	Expected Resource Cost
GDP	Gross Domestic Product
GHG	Greenhouse Gas
Gt	Gigatonne (10^9 tonnes)
IPCC	Intergovernmental Panel on Climate Change
MACC	Marginal Abatement Cost Curve
PPC	Perceived Private Cost
TEC	Techno-Economic Cost
US	United States
VES	Vehicle Emissions Standard

1. Introduction

The Intergovernmental Panel on Climate Change (IPPC) has stated that warming of the climate system is unequivocal, and is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. The IPPC has concluded with *very high confidence* that increased concentration of greenhouse gases in the earth's atmosphere since 1750 is one of the main causes of the increase in global average temperature, and that human activities have been the main source of these increased GHG emissions (IPCC, 2007). An international consensus was established with the United Nations Framework Convention on Climate Change that GHG emissions should be stabilized in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UN, 1992). Despite decades of international negotiations and attempts by many national governments to implement climate change policies, GHG emissions in most developed countries continue to rise.

The slow pace of progress is perhaps understandable. The world has never before faced a pollution problem of this scale. Global emissions in 2004 were 49 billion tonnes carbon dioxide equivalent (CO_2e). Every country, every sector, and every person contributes to these emissions. The scale of GHG pollution means the implementation of "low cost" solutions is crucial.

Countries and citizens have a limited tolerance to forego current economic prosperity for the benefit of future generations. For instance, many surveys of the U.S. public show about 50% of Americans are reluctant to support climate change policies that could increase their costs for energy services or increase unemployment (Nesbit and Myers, 2007). Leaders of the U.S. Republican party consistently oppose regulation of GHG emissions, referring to these regulations as "job-destroying" (Honig, 2011). Others emphasize that many low-cost emission reduction opportunities currently exist, and if the right policies are put in place, technological innovation will bring down the cost of reducing the remaining GHG emissions (Stern, 2007; Gore, 2009; Krugman, 2010).

The tension between economic vitality and reducing pollution pervades every environmental policy dialogue, but the scale of GHG emissions makes the tension all the more acute to climate change policy. Given the importance of low cost solutions, this study investigates cost-effective policy options for the United States, a country that has substantial influence on Canada's climate change policy and on international climate change policy.

A cost-effective policy is one that achieves the policy goal at the lowest cost to society. In other words, no other course of action could achieve the goal at a lower cost. Unlike a cost-benefit analysis, which calculates both the cost and the benefits of a policy, a cost-effectiveness analysis only estimates the cost of implementing the policy, thus side-stepping the controversial debates about how to value the highly subjective benefits of a policy (Stavins, 2011).

The valuation of the cost of a policy alone can also be quite controversial, as analysts employ different definitions of "cost" and different methodologies, both of which lead to widely disparate estimates (Fischer & Morgenstern, 2006; Jaccard, 2005a; Jaccard et al. 2003). Decision-makers and the public are then left either confused as to the valid estimate, or are left to cherry pick the estimate that best supports their interests and values.

Murphy & Jaccard (2011) use CIMS, a hybrid energy-economy simulation model to explain some of the roots of these disparate cost estimates as the extent of a model's representation of three characteristics: technological explicitness, behavioural realism, and macro-economic feedbacks. CIMS has the ability to apply policy costing methodologies that represent different application of these characteristics, and thus CIMS can be used to help understand the influence of these characteristics on estimation of policy cost.

This research project applies CIMS to compare the cost-effectiveness of different climate change mitigation policies for the United States, including the effects of different policy costing methodologies on the outcome. A cost-effectiveness study configures different policy approaches to achieve equivalent greenhouse gas (GHG) emission reductions. By holding GHG emission reductions constant, the cost of policies can be compared. The basic structure of this policy analysis is the comparison of sector-specific policies for the electricity and personal transportation sectors with each other, and against an economy-wide GHG emission tax policy.

The electricity and personal transportation sectors were chosen because these sectors are responsible for the greatest proportion of GHG emissions in the United States. In 2010, the electricity and personal transportation sectors were responsible for 34% and 27% of total GHG emissions, respectively (EPA, 2012). Considering these sectors together is also advantageous because any policy that induces greater adoption of electric vehicles will influence the GHG emissions in the electricity sector.

For the electricity sector, the policies compared are a technology regulation mandating the phase out of conventional coal and natural gas generation, and a clean electricity standard (CES) mandating that a certain proportion of total generation must emit zero GHG emissions. For the personal transportation sector, the policies compared are (1) a corporate average fuel economy (CAFE) standard mandating that new cars sold in a given year must achieve a fuel efficiency standard on average across a car manufacturer's fleet, and (2) a vehicle emissions standard (VES) mandating that new cars must achieve a GHG intensity standard (grams CO_2e emitted per kilometer driven) on average across a company's fleet. The CES, CAFE, and VES policies are all modeled to be tradable performance standards. Tradable performance standards mean that if a utility or a car company exceeds the standard, by either producing more zero-emission electricity or selling more efficient cars, those companies can sell performance standards to other companies that have not reached the standard.

In summary, the main research questions of this study are:

1. What is the cost-effectiveness of different policy instruments in achieving a given GHG emissions reduction target?
2. How do different policy costing methodologies influence the estimation of the total cost of a policy?

In addition to answering these research questions, a secondary objective of this paper is to convey the cost of these different policy approaches in terms comprehensible to the public at large. To put costs into context, the estimated cost of achieving GHG emission reductions is compared to the amount spent on achieving other social and private objectives.

Chapter 2 provides background on climate change policy instruments and discusses the different types of modeling approaches for estimating their cost. Chapter 3 describes the methodology used in this study to estimate policy cost, including a description of the model, CIMS, and the different measures of policy cost that can be generated through CIMS. Chapter 4 provides details on the calibration of CIMS-US, comparing CIMS' forecast for energy consumption and GHG emissions with the US Energy Information Administration's *Annual Energy Outlook*. Chapter 4 also outlines specific modeling assumptions relevant to this study. Chapter 5 provides the results of model simulations for ten different policy scenarios. The costs of these policy scenarios are compared using three different types of cost measures. Chapter 5 concludes with a section on "Putting Costs into Context". Chapter 6 discusses the major findings of this research study and recommendations for future studies.

2. Background

The objectives and methods of this research project are informed by two distinct, but interrelated, research areas. The first is the study of public policy, specifically the study of different policy instruments for achieving a policy goal and how decision-makers choose between these options. The second is the application of energy-economy models to provide information to decision-makers and the public on the impacts of different policy instruments. This section discusses both of these fields as they relate to this research project.

2.1. Public Policy and Climate Change Mitigation

The study of public policy tries to bring deliberate and objective analysis to the understanding and solving of public problems. This research project has benefited from two frameworks employed in public policy analysis (1) decision-making criteria for public policy, and (2) the categorization of policy options based on specific attributes, such as flexibility in compliance. Each of these frameworks will be discussed in turn below.

Decision-Making Criteria

To aid in choosing between policy instruments, decision-makers and policy analysts will often use evaluation criteria. Common criteria for environmental policies include effectiveness, administrative feasibility, political acceptability and cost-effectiveness (Jaccard, 2005b). While this research project is focused on the criteria of cost-effectiveness, the other three criteria have also been influential in the configuration of the policies in this study. For example, the study only evaluates policies that are thought to be effective at reducing GHG emissions. Policy instruments that are known to be less effective were not chosen, such as the provision of subsidies for consumers to buy more energy efficient devices (Loughran & Kulick, 2004). All of the policies are also known to be administratively feasible as they have all been implemented by democratic governments in a comparable form.

Consideration of the political acceptability of policies and the current political context of the United States was a major driver in the configuration of the study. Many academic studies have assumed that emission pricing, and more specifically a cap & trade program, will be the main instrument of choice to reduce greenhouse gas emissions in the United States, and have thus focused on research questions related to the design and implementation of such a system (Burtraw & Szambelan, 2009; Metcalf, 2009; Paltsev, Reilly, Jacoby, & Morris, 2009; Schakenbach, Vollaro, & Forte, 2009; Victor & Cullenward, 2007). For instance, Aldy et al. (2010) states plainly that “debate over the choice of instrument for a nationwide carbon control program is no longer about the superiority of market-based approaches over traditional forms of regulation (like technology mandates) but rather between the two market-based alternatives, emissions taxes and cap-and-trade systems”.

However, passing a climate change cap & trade bill or an equivalent economy-wide GHG tax in the United States appears to be a virtual political impossibility for the time being. Although the Democratic Party is in favour of policies to price GHG emissions, the Republican Party has lately turned against these policies. Given the division of powers in the US, the Democratic Party would then have to control the Presidency, the House of Representatives and the Senate to pass legislation providing an economy-wide mechanism to price GHG emissions.

This situation was almost present during the 111th congressional session (2008-2009), and the Obama Administration’s central strategy on climate change was the development of cap & trade legislation. During this congressional session, the Democratically controlled House of Representatives passed the cap & trade bill (H.R. 2454), but the bill could not get through the Senate because the Democratic Party did not have a supra-majority, which it needed to break Republican filibusters (Lizza, 2010). In the 112th Congress (2011-2012), the Democratic Party is in a substantially weaker position since the Republicans now have a majority in the House of Representatives and the Democrats have been reduced to 51 senators. The 112th Congress also contains an even stronger contingent of Republicans opposed to reducing GHG emissions. Of the

100 “freshmen” republicans in the 2011 House of Representatives, 50% deny the existence of manmade climate change, and 86% are opposed to any climate change legislation that increases government revenue (Keyes, 2010). However, some Republican congress representatives and senators are supportive of climate change legislation. Thus an opportunity exists for Democrats to negotiate with these Republicans to pass legislation.

Such a negotiation would expend significant political capital, which could explain why the Obama administration has decided not to pursue an economy wide GHG pricing policy, and is now turning to its executive powers over regulation to reduce GHG emissions. The President has the power to unilaterally make regulations to reduce GHG emissions through previously passed bills, mainly the *Clean Air Act*, which gives the Environmental Protection Agency (EPA) the authority to regulate emissions that present a danger to human health and the environment (Bianco & Litz, 2010).

The extent of this power to regulate is limited by the regulatory tools provided in the *Clean Air Act*, some of which are vague and open to legal interpretation. A clear authority exists to set emission performance standards for technologies, but whether these standards could be tradable at a sector level is unclear (Richardson et al., 2010, 18-20). Joe Aldy, former advisor to President Obama on Energy and Environment, recently stated in an interview with *Nature* that the *Clean Air Act* is not well designed for tackling climate change, and that the best way forward in the face of Republican opposition would be to try to pass a new piece of legislation mandating a clean energy standard in the electricity sector (Tollefson, 2011). Aldy was quoted earlier as inferring emissions pricing policies are the only option, so his revised opinion that a regulatory approach may now be preferable is indicative of the changing political conditions. Regardless of the legal ambiguity over whether new legislation would be needed or not, this study looks at both technology-specific and sector-level tradable performance standards as examples of more politically feasible policies.

Economic theory and economic modeling studies conclude that technology and sector-specific regulations will reduce GHG emissions at a higher cost than an economy-wide pricing mechanism, but by how much? Are there ways to make regulations more flexible and lower the costs? Given the current political context in the United States, these are the questions that this study pursues. As stated by Goulder & Parry (2008) in their analysis of climate change policy options:

> “no single instrument is clearly superior along all the dimensions relevant to policy choice...Significant trade-offs arise in the choice of instrument. In particular, assuring a reasonable degree of fairness in the distribution of impacts, or ensuring political feasibility, often will require a sacrifice of cost-effectiveness.”

While the focus of this study is on cost-effectiveness, this study does not presume that the best policy will be the most cost-effective. Rather, information on cost-effectiveness will be just one factor among many used to choose between policies. For instance, new research from psychologists (Bain et al. 2012) demonstrates how support for action on climate change is influenced by personal identity and values. This research finds that climate change skeptics are more likely to support action on climate change if action is framed in terms of producing greater interpersonal warmth or societal development rather than a frame focusing on the reality and risks of climate change. This finding suggests that regulations emphasizing technological progress to achieve cleaner electricity or higher efficiency cars could have a political edge above pricing policies focused purely on reducing emissions. Indeed, a recent poll of US public opinion on climate policy options found that Americans tend to be opposed to the emissions pricing policies most commonly endorsed by economists. Instead, Americans tend to be more supportive of regulatory programs related to energy development, industrial emission controls, and vehicle fuel efficiency (Borick and Rabe, 2012). These studies show how the economic cost of a policy may be less important than other personal values in determining one’s support for a policy.

Categorization of Policy Options

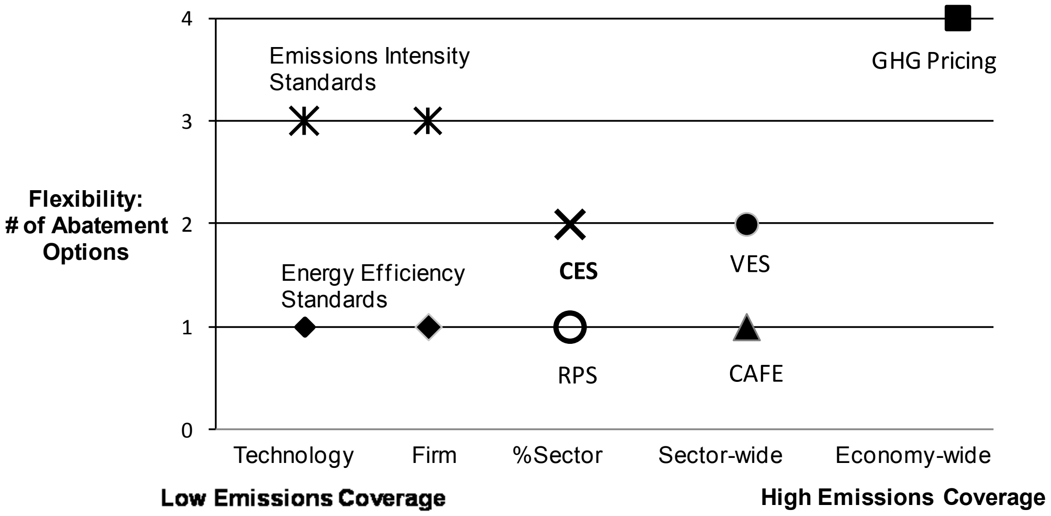
Policies can be categorized according to the flexibility of their compliance mechanisms and their coverage of emission sources. For this study, flexibility in compliance refers to the number of abatement mechanisms an agent can use to achieve the regulatory standard. The full spectrum of GHG abatement mechanisms available to society at large includes:

- Fuel Switching from fossi fuels to zero-emission fuels (renewables, nuclear)
- Energy Efficiency
- Carbon Capture and Storage
- Reducing demand for GHG-intensive goods and services
- Reduction in deforestation or other harmful land-use change activities

Thus emission reduction policies that can be met only through improving energy efficiency will be less flexible than policies that can be achieved through multiple ways such as fuel switching and energy efficiency. A policy's coverage of emission sources specifies if the policy is technology-specific, sector-specific or economy-wide. Flexibility and coverage are related to cost-effectiveness because the economic principle of equimarginality states that minimizing the cost of reducing a given amount of pollution requires equating marginal abatement costs across all options and agents for reducing pollution (Baumol and Oates, 1988). Thus the more emissions a policy covers and the more abatement options a policy allows for compliance, the more cost-effective a policy is expected to be.

To illustrate these attributes, Figure 1 depicts policies at different levels of flexibility and coverage. Along the X axis, policies are categorized according to their coverage of emission sources: technology specific, sector-specific or economy-wide. Along the Y axis, policies are categorized according to the number of ways they can induce emission reductions: including energy efficiency, fuel switching, carbon capture and storage, and reduction in demand for GHG-intensive goods and services. Deforestation was not included as an abatement option for this figure because it has traditionally been handled through policies specifically designed for its unique challenges. Note that Figure 1 is a simplified characterization of policy instruments to highlight the differences between the policies analyzed in this study. Standards and GHG pricing policies can be applied with more variability in their coverage than is depicted in this figure. For example, GHG pricing can be applied at the economy-wide level, or be limited to certain sectors.

Figure 1 *Flexibility and Coverage of GHG Abatement Policy Options*



Policies that fall in the lower left hand corner are expected to be the least cost-effective because they are the least flexible and have the least amount of emissions coverage. Policies in the top right corner are expected to be the most cost-effective. These policies are discussed below in order of their emissions coverage, beginning with technology-specific policies.

The conventional approach to mandating pollution reduction is through command and control policies, which force firms to take on similar shares of the pollution-control burden, regardless of the cost, by setting uniform performance standards at the technology or firm level. Technology performance standards require the installation of technologies that fall under a maximum amount of emissions or energy consumption per unit of output from the technology. As depicted in Figure 1, the technology standard provides the least amount of emissions coverage, covering just the emissions from that technology.

Performance standards at the firm level provide a bit more coverage by setting a standard for a level of pollution or energy consumption per unit output of a firm. Firms use numerous technologies, materials and processes to produce their output, thus these firms will have a multitude of options along their production chain to achieve a standard.

When setting these standards, governments typically use the best performing technology or firm currently in operation in the market place as a standard, and then require all other technologies or firms to meet this standard. Technology and firm standards can inhibit technological innovation as firms typically have no incentive to beat the standard (Millliman & Prince, 1989). For instance, if the government sees a firm deploying an innovative technology, the government may force that company to implement that technology in all operations.

Technology- and firm based standards can be set up as either energy efficiency standards or emissions intensity standards. Both have the potential to reduce overall greenhouse gas emissions, but at differing levels of compliance flexibility. Consider the differences in abatement opportunities for each of these standards in the case of a coal generation plant. While the only way for a coal plant to meet an energy efficiency standard is to reduce their consumption of coal per kilowatt hour of electricity, a coal plant could meet an emissions intensity standard in multiple ways. In addition to improving their energy efficiency, the coal plant could pursue fuel switching to retrofit their boilers to consume biomass, or the coal plant could retrofit their plant to enable carbon capture and storage. Since each coal plant will have their own unique set of circumstances, the presence of options for meeting a standard allows the coal plant to pursue the least costly option.

In addition, these two types of standards have different effects on the supply and demand of GHG-intensive goods. By increasing energy efficiency, an energy efficiency standard will often lower the cost of consuming a good or service, and will thus encourage an increase in its supply and demand, a dynamic termed the “rebound effect”. An emissions intensity standard side-steps the complication of rebound effect by directly targeting the problem: emissions. Targeting emissions will lower demand for GHG-intensive goods and services by increasing their cost relative to lower GHG-intensive goods and services. Thus while energy efficiency standards are quite limited in having only energy efficiency as an abatement option and are subject to this negative rebound effect, emissions intensity standards allow all four of the abatement options.

Returning to the issue of emissions coverage, performance standards for firms mandate compliance of all firms to a uniform standard, and thus cost-effectiveness is undermined to the extent that firms face different costs for compliance. Across firms, costs can vary enormously due to production design, physical configuration, and age of assets. Mandating all firms to achieve the same target will result in higher than necessary abatement costs across the whole sector (Stavins, 2011).

To summarize, the drawbacks of technology- and firm-specific standards are twofold: they impose the highest costs for achieving a given amount of pollution reduction and they inhibit technological innovation (Aldy & Stavins, 2011). However, since these standards have been the conventional approach of governments, they tend to be the most politically feasible. Governments have a demonstrated legal authority to impose these standards, and since they are usually imposed on businesses, they go under the radar of the voting public.

Tradable performance standards lower costs and encourage innovation. These standards are met on average across a sector, allowing individual firms the flexibility to not meet the standard and buy credits from firms who have exceeded the standard. Figure 1 shows four types of tradable performance standards: renewable portfolio standard (RPS), clean electricity standard (CES), corporate average fuel economy (CAFE) standard, and a vehicle emissions standard (VES). Similar to the technology and firm examples, the policies that are formed as emission standards enable greater abatement options than focusing a standard on an attribute related to emissions such as fuel type or energy efficiency. For example, a corporate average fuel economy standard will result in emission reductions only through the improvement of energy efficiency, while a vehicle emissions standard can be met through improving energy efficiency, selling more zero-emission cars (electric and biofuel), or even through improving vehicle air conditioning systems.

A renewable portfolio standard mandates that a certain percentage of a utility’s generation be from renewable sources, such as wind, solar, geothermal, hydro, and biomass. While a technology-specific policy would mandate or encourage the use of one of these renewable electricity technologies over the others, an RPS allows a utility to choose the renewable technology that is best for its situation, and also allows the utility to buy renewable generating credits from another firm that has exceeded the standard. As a policy to achieve emission reductions however, the RPS excludes several abatement options. Firstly, the RPS only covers a portion of total generation, thus the other portion could still have very high emissions intensity with no requirement to reduce emissions through methods such as fuel efficiency. Secondly, the RPS does not include other near zero-emission generation technologies such as nuclear power and carbon capture and storage (CCS). The clean electricity standard differs from the RPS by allowing the use of nuclear and CCS power to count towards the required percentage of total generation. Thus while the RPS relies on fuel switching from fossil fuels to renewable energy, the clean electricity standard allows for fuel switching to renewable and nuclear energy, as well as allowing fossil fuel generation with CCS.

Comparing the cost of sector-wide and technology-specific policies based purely on their flexibility and coverage is only appropriate within sectors and not across sectors. For example, Aldy et al. (2010) conclude that achieving emission reductions in the personal transportation sector has higher marginal costs than the electricity sector, meaning for any given percentage target of emission reduction, the electricity sector could reach the target at a lower cost than the personal transportation sector. Thus a technology regulation on coal plants could be less costly than a vehicle emissions standard, even though a VES has wider coverage and similar level of abatement options.

Another consideration with sector-specific policies is their effects on emissions in other sectors. For example, both a CAFE standard and a VES standard are likely to lead to increased electricity demand since electric vehicles are both higher in efficiency and lower in emissions than the combustion engine. Consequently, in the absence of GHG reduction policies in the electricity sector, these transportation policies could lead to increased total emissions. In the most extreme case, the increased electricity demand from the transportation policy could be met with new coal-fired generation.

The only ways to reduce these inter-sector effects is either through implementing policies in each sector simultaneously or through implementing an economy-wide policy pricing GHG emissions. According to the economic principle of equimarginality, the most cost-effective policy puts a price on emissions across the whole economy, so that every actor faces an equivalent price for emitting (Baumol and Oates, 1971). GHG emission pricing can be achieved through either taxing GHG emissions or establishing a GHG emissions cap & trade system. These policies can be applied across multiple sectors or to all emissions in an economy, offering the greatest emissions coverage. They also take advantage of all abatement options, providing the greatest flexibility.

The economist rationale behind taxing pollution is based on classifying pollution as a negative externality, meaning an unintentional consequence of production or consumption that reduces another agent's utility. Polluters benefit from having free access to dump their waste products into a common "sink", but everyone in society incurs a cost from the harm caused by this pollution. Pigou (1920) was the first to suggest that these externalized costs to society be internalized on the polluter through imposing a pollution tax. Such a system means firms have an incentive to reduce emissions to the point where their marginal abatements costs are equal to the tax rate. They also have a further incentive to innovate and reduce the residual emissions that are being taxed. Such a tax is administratively easy to implement for fossil fuels because when burned, each type of fossil fuel releases a standard amount of CO_2 emissions.

Instead of classifying pollution as a negative externality that needs to be taxed, pollution can also be thought of as resulting from poorly defined property rights. For example, no one owns the atmosphere; it is an open access common resource and is thus vulnerable to being taken advantage of by polluters. Access to a common resource can be restricted by a government through assigning property rights for emitting pollution and allowing these rights to be traded in a market, a mechanism called cap-and-trade. This mechanism sets a cap for allowable emissions of a pollutant and then distributes emissions permits in line with this cap. The government can either distribute these permits through auctioning, allocating them freely to firms, or a combination of both. Regulated firms must surrender permits equal in value to the emissions for which their activities are responsible. The permits may be bought and sold, allowing firms with high abatement costs to purchase permits from firms with low abatement costs. The trading market for permits then reveals the effective marginal price for emitting (Metcalf, 2009; Stavins, 2011).

A large literature exists comparing the pros and cons of an emissions tax against a cap-and-trade system, but largely these differences relate to the political acceptability and administrative feasibility of one instrument over the other (Stavins, 2011). In terms of cost-effectiveness, a cap-and-trade system with auctioned permits is expected to result in virtually the same abatement cost as a GHG tax with the same emissions coverage. The revenue from a GHG tax or auctioned permits can be recycled back into the economy through lowering personal income or corporate taxes, or by investing it in public infrastructure and services.

A cap-and-trade with freely allocated permits will be less cost-effective than an emissions tax or a cap & trade with auctioned permits. Since permits have a value in the permit market, freely allocating these permits to polluters is equivalent to giving a subsidy to a polluting industry, lowering that industry's production costs and making it profitable to increase production. But a cap-and-trade with freely allocated permits will still be more cost-effective than a non-pricing policy.

This section has provided a brief introduction to the spectrum of policy options for reducing GHG emissions. Virtually every country in the developed world has chosen some combination of policies to reduce GHG emissions. Each country's choice is influenced by their particular political and economic circumstances, which subsequently determines how each policy fares when evaluated under the criteria of political and administrative feasibility. Generally speaking, the effectiveness and cost-effectiveness of policy instruments are similar across countries. The following section discusses how these different types of abatement policies are being implemented or considered in the United States.

2.2. Current Policies of US Federal Government

In the 2007 Supreme Court Case Massachusettes vs. EPA, the court ruled that GHG emissions are considered air pollutants under the existing *Clean Air Act* and therefore must be regulated by the Environmental Protection Agency (EPA) if they endanger human health and welfare. In December of 2009, the EPA issued their final finding that GHG emissions threaten the public health and welfare of American people, and that GHG emissions from on-road vehicles contribute to this threat. This finding was a legal requirement in the Clean Air Act to proceed with implementing GHG standards on light-duty vehicles (EPA, 2009).

In line with the Supreme Court ruling, the Obama Administration committed to reduce GHG emissions at the international level through the 2009 Copenhagen Accord. The U.S. committed to a greenhouse gas (GHG) emissions reduction target of 17% below 2005 emission levels by 2020, 42% reduction by 2030, and 83% reduction by 2050 (Department of State, 2010). As of June 2012, the Obama administration has approved some measures to reduce GHG emissions in the personal transportation sector, and policies for the electricity sector are still in development.

Transportation Sector

The Obama Administration has been very active in proposing and finalizing fuel economy and GHG emission standards for vehicles. Their approach for these standards can be classified as tradable performance standards within the broad vehicle categories of light-duty vehicles and heavy-duty vehicles. Performance standards can not be traded between certain vehicle categories, but they can be traded within categories.

The National Highway and Traffic Safety Administration (NHSTA) and the EPA are working jointly to implement these standards because the NHSTA is the designated authority to implement vehicle fuel economy standards under the *Energy Policy and Conservation Act* (EPCA) and the EPA is the designated authority to implement GHG emissions standards for vehicles under the *Clean Air Act.* EPA has finalized GHG emission standards for light-duty vehicles in model years 2012-2025. For model year 2025, the finalized standard requires, on an average industry fleet wide basis, 163 grams CO2 /mile, equivalent to 54.5 mpg if all of the CO_2 emission reductions were achieved with fuel economy technology. NHTSA still needs to publish finalized standards for fuel economy, but their proposal would require, on an average industry fleet wide basis, 40.9 mpg in model year 2021, and 49.6 mpg in model year 2025 (EPA & NHTSA, 2011a, 7-8). These agencies explain that the NHTSA fuel economy standards are lower than the EPA standards for reasons of harmonization because statutory constraints in the *Energy Policy and Conservation Act* do not allow NHTSA's standards to include air conditioning system refrigerant and leakage improvements. The agencies also state that they believe these standards can be met with improvements in conventional gasoline and hybrid vehicle technologies and an increased market share of more advanced technologies including electric vehicles and plug-in hybrid vehicles.

The NHTSA states that consumers who buy vehicles that can use 85% ethanol in their fuel (E85 fuel) fill their vehicles with E85 fuel a small percentage of the time, thus their treatment of E85 vehicles for purposes of complying with the standards will be based on real-world usage of E85 fuel (EPA & NHTSA, 2011a, 17).

The fuel economy and GHG standards for model years 2012-2025 have similar flexibility provisions for compliance. Vehicle manufacturers can earn credits for exceeding the standards of a vehicle category (passenger cars and light-duty trucks). EPA allows for the unlimited transfer of these credits between the categories of passenger cars and trucks, while NHTSA allows for transfer of these credits up to a statutory limit. For both the EPA and NHTSA standards, the credits can be carried forward for five years, carried back for three years, or traded with other manufacturers (EPA & NHTSA, 2011a, 17-18).

In August 2011, the Obama Administration finalized fuel efficiency standards for heavy-duty engines and vehicles for model years 2014-2018. Fuel efficiency and GHG emission standards have been set for the three major categories of heavy-duty vehicles: combination tractors (semi-trucks), heavy-duty pickup trucks and vans, and vocational vehicles (such as transit buses and refuse trucks). Companies will have similar flexibilities in complying with the standards as manufacturers of light-duty vehicles. The flexibility provisions allow for engine averaging, banking and trading within each of the regulatory subcategories, but not across subcategories (NHTSA & EPA, August 2011).

Electricity Sector

Once any substance becomes a regulated pollutant under the *Clean Air Act*, new or modified sources of the pollutant become subject to a new source review permitting process. A tailoring rule limits the reach of the new source review permits to new stationary sources that would emit at least 100,000 tons per year of CO_2e or major modifications of existing sources that would emit at least 75,000 tons per year of CO_2e. The implementation of GHG standards for motor vehicles triggers these new source review requirements for major new sources and major modification of existing stationary sources that occur after January 1, 2011 (Pew Center, 2010).

When the EPA failed to act on these obligations under the *Clean Air Act,* several states, local governments and environmental organizations sued the EPA over their failure to update the new source review permits for fossil fuel power plants and petroleum refineries, two of the largest source categories of GHG pollution in the United States. The EPA negotiated a settlement agreement with these parties to propose standards for power plants in July 2011 and for refineries in December 2011 and will issue final standards in May 2012 and November 2012, respectively. As of July 2012, the EPA is behind schedule and has only proposed new source performance standards for electricity. Their proposal would limit CO_2 emissions from new fossil-fuel fired electricity generating units greater than 25 megawatts to 1,000 pounds per megawatt-hour, a level based on the CO_2 emissions from natural gas-fired combined cycle units (NGCC) (Gibson, 2012).

Despite the delay, final performance standards for the electricity and petroleum refining industries appear to be imminent. However, the election of a Republican President could through them off track in November 2012. Regardless, for the purposes of this study, the key consideration is that the policy instrument the US government is pursuing for the electricity sector is a firm-specific performance standard for new power plants only, one of the least cost-effective of the instruments reviewed in Section 2.1.

2.3. Rationale for Policy Choice in this Study

The most politically feasible option for the US government to mandate GHG emission reductions in the electricity sector is firm-specific emissions standards. Indeed, this seems to be the route that the current US government is taking. To investigate the cost-effectiveness of this approach, this study compares a firm-specific performance standard for the electricity sector with a tradable performance standard. The firm-specific policy prohibits installation of new coal-fired generation from 2016-2050 and natural gas generation from 2031-2050, unless these plants utilize carbon capture and storage technology that capture 90% of their GHG emissions. This emissions standard for firms is compared to a tradable performance standard, specifically a clean electricity standard (CES), which mandates that a certain percentage of generation within the electricity sector be from zero-emission sources. A CES is chosen over a renewable portfolio standard (RPS) because, for all of the reasons discussed in Section 2.1, a CES is likely more cost-effective than an RPS.

For transportation, I chose to compare the cost of two types of tradable performance standards – corporate average fuel efficiency standard and a vehicle emissions standard. I am only comparing tradable performance standards for this sector because these are the types of policies currently being implemented by the US federal government, thus they are unlikely to consider technology or firm specific policies in the future for this sector. The US federal government is currently implementing both a CAFE standard and a vehicle emissions standard, which is a questionable approach from the perspective of GHG emission reduction since only one of these policies is necessary to achieve this goal. Of course, the foremost stated goal of the CAFE standard is to reduce dependence on foreign oil, but a vehicle emissions standard would also reduce oil consumption and should theoretically be more cost-effective at reducing emissions than a CAFE standard. Thus arguably the US should only implement one of these tradable performance standards, and should choose the standard that reduces oil consumption and GHG emissions in the most cost-effective manner.

To facilitate the evaluation of the cost of these firm- and sector- specific abatement policies, I found an economy-wide GHG tax that is estimated by the model to reach equivalent levels of GHG emission reductions. The revenue from the GHG tax is then returned to each sector in proportion to how much each sector contributes, and firms within a sector receive their share of the recycled revenue according to an unbiased formula, such as a firm's output. This GHG tax schedule can be considered equivalent to a cap-and-trade policy whereby emissions are capped at the same level as the emission reductions from a firm- or sector-specific policy and permits are distributed through an auction. A GHG tax and an auctioned cap & trade are just two different paths to the same destination. When emission reductions under a GHG tax or under a cap-and-trade are equivalent, then the effective price on emitting is also equal. Furthermore, when the price of emitting and emission reductions are equivalent, as then can be under a GHG tax or cap-and-trade, then the total cost of a policy is also equal (Metcalf, 2009;

Weitzman, 1974). Thus for the purposes of a cost-effectiveness study, these policies can be considered interchangeable.

The total cost of implementing these firm, sector, and economy-wide policies can be estimated through energy-economy models. The next section provides background on the different types of energy-economy models and how they can be used to simulate the implementation of policies in an economy.

2.4. Energy-Economy Models for Environmental Policy Analysis

Energy-economy models can be used to estimate the environmental and economic impact of policies that affect energy consumption and production. This study uses a hybrid energy-economy model to simulate policies to induce GHG emission reductions. The term “hybrid” originates because the model draws from two other categories of models: (1) bottom-up technology models, and (2) top-down models. Each of these categories of models has strengths and weaknesses in estimating and describing the impacts of environmental policy. In many cases, the strength of a bottom-up model is a weakness of a top-down model, which is why hybrid models developed to take advantage of the strengths of both bottom-up and top-down models (Jaccard, 2009). The common link between bottom-up, top-down and hybrid models used to analyze climate change mitigation is that they all model interactions between energy, the environment and the economy. They differ with respect to the following key attributes: (1) technological explicitness (2) behavioural realism, (3) macro-economic feedbacks.

Conventional bottom-up models include a broad set of technologies that can be substituted for one another to meet energy service demands. Most of these models are optimization models that choose a technology mix to optimize a certain goal, such as reducing emissions at the lowest financial cost, subject to certain constraints, such as emission levels (Loschel, 2002). The strength of bottom-up models lies in their technological richness, allowing for new technologies and technological innovation to be directly considered. Their high level of technological detail also allows for a better “picture” of how the future may evolve under various policy regimes.

While these models have the advantage of being technologically detailed, they lack behavioural realism, which refers to a model's ability to represent the behaviour of firms and consumers. Conventional bottom-up models treat technologies that deliver a similar service as perfect substitutes and compare substitutable technology only on their direct financial costs and emissions. In reality, one technology is often not a perfect substitute for another technology, and firms and consumers consider much more than just financial cost when making technology choices. These other costs, described in further detail in Section 3.2, include intangible costs such as risk of technology failure, and consumer values such as convenience, aesthetics, and reliability.

Top-down models are a mirror image of bottom-up models. They lack technological detail but they are better at incorporating behavioural realism. Top-down models estimate aggregate relationships between energy and other inputs into the economy based on their relative costs and the degree of substitutability between inputs to produce economic output. Elasticity of substitution (ESUB) parameters are used in top-down models to describe how factors of production are substituted for one another when their relative prices change. The degree to which a policy results in a shift away from carbon emitting inputs depends on the elasticity of substitution between alternative inputs, or in other words, the ease at which low-to zero emitting inputs can be substituted for high emitting inputs (Ramskov & Munksgaard, 2001).

In addition to being more behaviourally realistic, top-down models often incorporate macroeconomic feedbacks, a feature that conventional bottom-up models do not include. For instance, an increasingly popular type of top-down model, the computable general equilibrium (CGE) model, will balance the supply and demand of goods when changes occur in the price of factors of production such as capital, labour and energy. Conventional CGE models assume that the economy is in equilibrium in the model's base year and in the business as usual (BAU) projections from the base year. When a policy is then simulated in the model that affects the relative prices of factors of production, the modeled economy is put into dis-equilibrium. The model then calculates a new equilibrium point by finding a new set of prices based on elasticity of substitution parameters, and a new level of consumption and production based on supply and demand functions (Bergman and Henrekson, 2003).

The differences between bottom-up and top-down models are significant because they often come to vastly different conclusions about the cost of greenhouse gas abatement. Bottom-up technology models often conclude that substantial GHG emission reductions are possible at little or no extra cost compared to a business as usual scenario (McKinsey&Company, 2009). In contrast, since conventional top-down models assume the economy is in equilibrium in the business as usual scenario, any policy that moves the economy away from equilibrium imposes a cost to society.

Hybrid models take the design strengths of both bottom-up and top-down models to make a model that integrates technological explicitness, behavioural realism and macro-economic feedbacks. This study uses a hybrid energy-economy simulation model, CIMS, which originated as a bottom-up technology model and then was modified to include design features of top-down models.

Murphy & Jaccard (2011) explore the differences between the McKinsey bottom-up model and a hybrid model, CIMS. When CIMS is run with its normal settings, it produces a higher abatement cost curve than McKinsey. As well, McKinsey finds the majority of emission reductions are a result of increasing energy efficiency, while CIMS finds emission reductions come from a mixture of fuel switching and energy efficiency. Through turning off the macroeconomic feedbacks and behavioural realism within CIMS, Murphy & Jaccard (2011) were able to reproduce an abatement cost curve similar to McKinsey's model, demonstrating the reasons why these models produce different results.

Through focusing just on financial technology costs, the McKinsey model generates optimism for the potential of energy efficiency in reducing emissions. But this optimism may be misplaced because the model does not actually represent how firms and consumers make their decisions, and the model doesn't include macro-economic linkages (Murphy & Jaccard, 2011). Politicians are tempted by the conclusions of bottom-up models like McKinsey, seeing an opportunity to generate economic savings and reduce emissions through increasing energy efficiency. However, policies that place too much emphasis on energy efficiency will not actually produce the promised emission reductions because this promise is based on conclusions from the flawed methodology of bottom-up models. This example of McKinsey vs. CIMS demonstrates the importance of incorporating behaviour and macro-economic feedbacks, and also more generally, shows the importance of critically evaluating energy modeling methodology.

Variation across Energy-Economy Models

To be clear, the difference in the structure between bottom-up, top-down, and hybrid models is not the only factor causing divergent cost estimates. Substantial variation in cost estimates exists within each category of model type as well. The only way to determine why models get disparate results is to compare results from different models that are operating under a similar set of assumptions. The Energy Modeling Forum (EMF) run out of Stanford University is a leading institution that organizes these types of cross-model comparisons. One such comparison is EMF-16, which completed its study in 1999 on estimating the costs of the US to reach their Kyoto commitments with various levels of international trading. This comparison, containing mostly top-down models, had cost estimates that varied by a factor of five or more (Weyant, 2008).

Fischer & Morgenstern (2006) examined the variation in abatement cost curves for models participating in EMF-16, which included mostly CGE models and a few hybrids. In this study, econometric analysis was used to measure the influence of certain model characteristics on a model's estimation of abatement cost. Fischer & Morgenstern (2006) found the following model characteristics to be significant in explaining variation in abatement costs across models: (1) the presence of a backstop technology, (2) the number of regions and number of sectors, and (3) the framework for modeling international linkages, such as perfect mobility versus Armington assumptions. While these findings indicated areas for further research, they could not draw conclusions on which model configuration is more "correct" in estimating abatement costs. The authors concluding statement is illustrative of the state of current knowledge with respect to explaining the variation amongst models:

> Collectively, large and small modeling choices form a black box that calculates abatement costs. The same black box calculates baseline emissions and thereby abatement requirements, making cross-model comparisons more difficult. In principle, one can open the box and seek detailed information across models about key modeling and parameterization choices...Arguably, our ability to interpret the effects of broader structural choices in climate models is hampered by the lack of specific information about such choices (Fischer & Morgenstern 2006).

CIMS enables some light to enter the “black box” of abatement costs because its flexible hybrid structure allows the calculation of abatement costs with a bottom-up methodology or a top-down methodology. Although CIMS does not have the full general equilibrium capabilities of most top-down models since it only balances energy supply and demand markets. The technological detail within CIMS also allows for more comprehensive explanations of modeling results than can be achieve with top-down models. The following sections describe CIMS and the methodology employed in this study to calculate abatement costs using CIMS results.

3. Methodology

The methodological component of this study can be broken into two parts. Firstly, climate change policies are simulated using CIMS, a hybrid energy-economy model developed in the Energy and Materials Research Group (EMRG) at Simon Fraser University. Secondly, the total cost of each climate change policy is calculated from results of CIMS' simulations. Section 3.1 gives a general overview of CIMS, including a description of the following key attributes in the model: (1) technological choice and innovation, (2) behavioural realism, (3) macro-economic feedbacks. Section 3.2 describes the three measures by which total abatement costs are calculated with CIMS results.

3.1. Hybrid Energy-Economy Model: CIMS

Characteristic of bottom-up models, CIMS has a detailed representation of energy service demands in an economy (such as heated commercial floor space or person-kilometres-travelled). CIMS then has a detailed representation of the energy technologies that can be used to meet these services. For each service, technologies with variable characteristics compete to meet demand (Rivers and Jaccard, 2006).

A CIMS simulation begins in 2000 and runs in five-year periods until 2050. In each period, the model follows these five steps in sequence (Bataille, 2005) :

1. *Assessment of Demand:* Demand for services from each sector is determined through modifying an exogenous forecast with information from the macro module if the price of the service has changed.
2. *Retirement and Retrofit:* Technology stock from the previous period is selected for retirement according to an age-dependent function. These technologies can either be fully retired or retrofitted. The difference between the residual capacity and the demand for service is the level of new technology stock that needs to be acquired.

3. *Competition for New Stock:* At each service node, technologies compete for new market share based on a market share algorithm (explained below).
4. *Equilibrium of Supply and Demand:* Once forecasted demand has been satisfied, the model iterates between the energy supply and demand modules until equilibrium prices for energy are found.
5. *Output:* The model generates values for energy consumption, GHG emissions, economic factor costs, and service output. The scale of this output ranges from economy and sector-wide to technology-specific.

The market share algorithm is the core function in CIMS that determines which technologies gain market share for delivery of a service. The function, as seen in Equation 1, compares the life-cycle costs (LCC) of one technology to its possible substitutes, and applies a variance parameter, *v,* to represent the heterogeneity in costs of technologies in the marketplace.

Equation 1

$$MS_j = \frac{\left(LCC_j\right)^{-v}}{\sum_{k=1}^{K}(LCC_k)^{-v}}$$

A high value for *v*, such as 100, means that the technology with the lowest life-cycle cost captures almost all of the new equipment stocks. An extremely low value for *v*, such as 1, means that new equipment market shares are distributed almost evenly between all competing technologies, even if their life-cycle costs differ significantly. Thus, *v* represents sensitivity of the technology competition to relative life-cycle costs. The default value for *v* is 10, meaning that where a technology has an *LCC* advantage of at least 15% over its competitor(s) it would capture at least 80% of new stock.

A technology's life-cycle costs, calculated through Equation 2, includes financial costs (capital, operating, energy, emission), and intangible costs or benefits.

Equation 2

$$LCC_j = \frac{\left(CC_j + IC_j\right) * \frac{r}{1-(1+r)^{-n_j}} + O\&M\ Cost_j + Energy\ Cost_j + Emissions\ Cost_j}{Total\ Output_j}$$

CC_j = Capital Cost for technology ‘j’

IC_j = Intangible Cost for technology ‘j’

r_j = revealed discount rate for technology ‘j’

n_j = life of technology for technology ‘j’

The intangible cost parameter is one method CIMS employs to represent behavioural realism. This parameter represents the fact that a technology may not always be a perfect substitute for another technology, even though it delivers an equivalent service. For example, an energy efficient washing machine may have cheaper financial costs but it takes double the amount of time to do a wash, thus a consumer may perceive this extra time as an additional cost. Or a firm may perceive a new innovation as higher risk due to a lack of production experience.

Another behavioural parameter in CIMS is revealed discount rates. Bottom-up models annualize capital costs using a social discount rate based on the cost of borrowing money from a bank, ranging from 5-10%. In CIMS, capital costs and upfront intangible costs are annualized by a higher “revealed” discount rate, based on observed behaviour of consumers and firms when they make capital investment decisions.

Over the years, EMRG has made a concerted effort to empirically estimate key behavioural parameters using discrete choice models. The data for these models can be acquired from revealed preferences in market transactions or from the stated preferences in a discrete choice survey. Studies on revealed discount rates, intangible costs, and the v parameter, have been completed for personal transportation (Horne, 2003; Axsen *et al.* 2009) , thermal technologies in industry (Rivers & Jaccard, 2005), and residential energy choices (Sadler, 2003). When a specific study has not been completed, behavioural parameters are set through literature review or through calibrating the model to historical data. See Appendix 1 for the discount rates used in the US version of CIMS.

When simulating the development of energy systems over decades, the incorporation of technological innovation becomes a key modeling consideration. In CIMS, innovation is represented by declining capital costs of abatement technologies as their cumulative production increases over time. CIMS uses a declining capital cost function to link a technology's capital cost in future periods to its cumulative production. The capital cost of a technology declines according to Equation 3 where *C*(*t*) is the financial cost of a technology at time *t*, *N*(*t*) is the cumulative production of a technology at time *t*, and *PR* is the progress ratio, defined as the percentage reduction in cost associated with a doubling in cumulative production of a technology. Progress ratios are calculated from empirical evidence of the historical relationship between capital cost and cumulative production. Typically, progress ratios range from 75 to 95 percent (Jaccard, 2009). A progress ratio of 75% means that when a technology's production doubles, the capital cost is expected to be 75% of the original capital cost.

Equation 3 Declining Capital Costs

$$C(t) = C(0)\left[\frac{N(t)}{N(0)}\right]^{\log_2(PR)}$$

Early modeling efforts approximated learning curves by decreasing cost only as a factor of time. When such models were used to evaluate when GHG abatement actions should be taken to reach a target, they recommended delaying abatement actions since delayed actions were cheaper. However, for most products and services, the passage of time is not what makes them cheaper. Rather, the capital costs of technologies decline as their production grows due to experience and economies of scale (Loschel, 2002; McDonald & Schrattenholzer, 2001).

The "neighbour effect" is another dynamic that occurs with increased production and consumption of a new technology. Research shows that as information on a technology's performance becomes more readily available, perceptions of risk are lowered. In other words, as your "neighbours" start using a technology, knowledge of that technology increases and risks are lowered, thus making it less costly to acquire that technology. To simulate this dynamic, CIMS has a declining intangible cost function that links the intangible costs of a technology in a given period with its market share in the previous period. Intangible costs are modeled to decline according to Equation 4, where *i*(*t*) is the intangible cost of a technology at time *t, i*(*fixed*) is the portion of initial intangible cost that is static, *i*(0) is the variable portion of intangible cost at time period 0, $MS_{t\text{-}1}$ is the market share of the technology at time *t*-1, and *A* and *k* represent the curve and rate of change of the intangible cost in response to increases in the market share of the technology (Axsen et al., 2009).

Equation 4   Declining Intangible Cost

$$i(t) = i(fixed) + \frac{i(0)}{1 + Ae^{k*MS(t-1)}}$$

Macro-economic feedbacks are another key dynamic process in CIMS. Macro-economic feedbacks refer to changes in supply and demand as a result of changes in prices. Climate change policies will often increase the cost of meeting a given energy service, since more expensive technologies will replace lower cost GHG-intensive technologies. Increasing the cost of an energy service then decreases the demand for this service. For instance, consider the macro-economic feedbacks involved in a policy to phase-out coal generation and increase renewable generation. In replacing coal generation with higher cost renewable generation, the price of electricity increases, causing a decrease in demand for electricity. In addition, the demand for coal would also decrease, lowering the output of the coal mining sector.

Most top-down models used today are general equilibrium models, meaning the supply and demand across all sectors of the economy are balanced as prices change. CIMS is only a partial equilibrium model, with a focus on balancing supply and demand for energy related services. CIMS does not equilibrate government budgets and the markets for employment and investment (Jaccard *et al.,* 2004).

In summary, CIMS takes advantage of the best attributes of both bottom-up and top-down models to estimate the environmental and economic impact of a climate change policy. The following section describes the different ways economic impact can be assessed using CIMS results.

3.2. Measures of Policy Cost

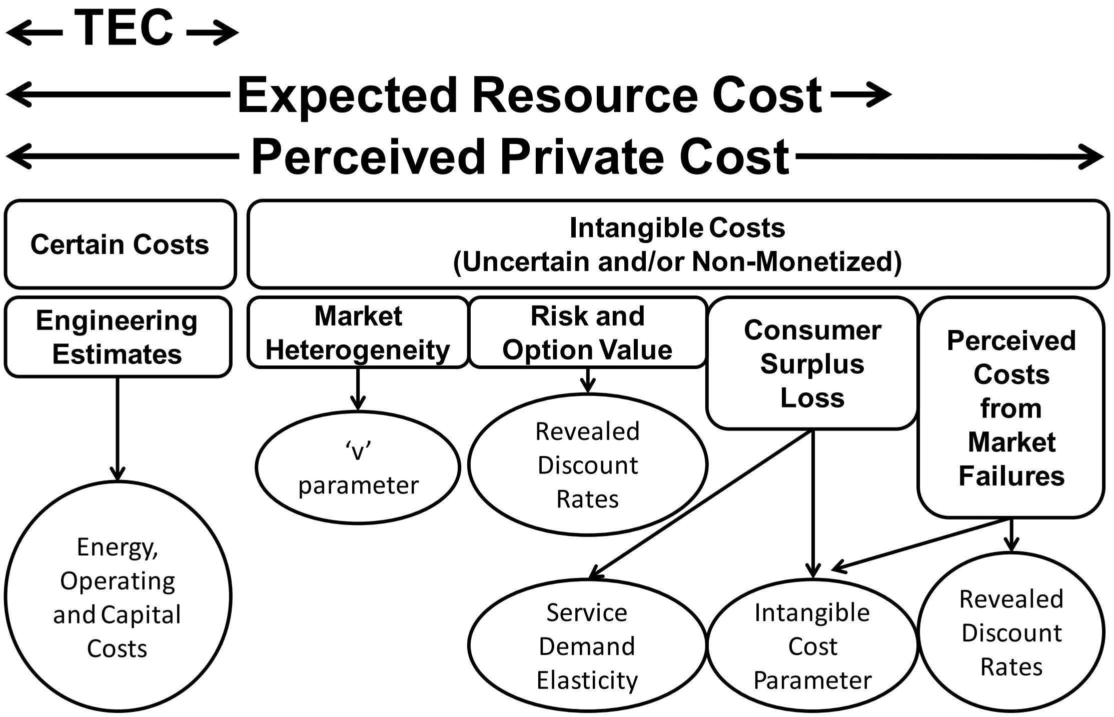
The “cost” of a pollution abatement policy refers to the cost of inducing or forcing consumers and firms to switch away from a technology or behaviour that they would otherwise choose. Bottom-up and top-down models apply different definitions of "cost" and therefore make very different estimates for how much a policy will cost to implement.

G. Box, a simulation modeler, is quoted as saying "while all models are wrong, some are more useful". Jaccard et al. (2003) state that for models to be useful in costing GHG reduction, they need to help policy-makers understand the key factors behind divergent cost estimates. CIMS is useful in this respect because it can be used to produce cost estimates consistent with the definition of cost employed in a bottom-up or a top-down model. Namely, three cost measures can be produced with results from CIMS (1) techno-economic cost (2) perceived private cost, and (3) expected resource cost.

To understand how these measures differ from each other, the concept of "cost" must first be broken into smaller components. Figure 2 depicts the components of costs in boxes, and the parameter(s) representing each cost component in CIMS are indicated in circles. "Cost" can first be separated into "certain" costs and "intangible" costs.

"Certain" costs are those that can be estimated before an investment is made (*ex ante*) with a fair degree of certainty through engineering estimates of expected capital, operating and energy costs. However, *ex ante* engineering estimates of financial cost have been found to consistently underestimate *ex poste* financial costs of a technology because they only consider those costs that are absolutely certain, and leave out costs that have a probability of occurring or are non-monetized. While engineering estimates may often leave out these intangible costs, firms and consumers will regularly perceive them as real "costs" (Jaffe & Stavins, 1994). Consequently, engineering estimates will often overestimate the adoption of a new technology because they only contain a partial representation of "cost".

Figure 2 Components of Policy "Cost"



CIMS aims to be a behaviourally realistic model and thus uses both certain and intangible cost attributes to simulate technology choice. Intangible costs are more difficult to quantify because firms and consumers perceive these costs with varying magnitudes and probabilities. Within the CIMS framework, intangible costs are divided into five categories – (1) market heterogeneity, (2) risk (3) option value (4) consumer/firm preference (5) perceived costs from market failures.

Market heterogeneity refers to costs that are specific to the individual circumstances of firms and consumers, such as installation and operating costs, which can vary by location and type of facility or household (Jaccard, 2005, 95). For example, a company considering whether to switch from a technology fueled by oil to one fueled by natural gas will face varying levels of cost depending on the surrounding natural gas infrastructure. Likewise, a consumer contemplating geothermal heating for their house will face lower costs if their house is built on soil than if it is built on rock. When simulating the technology choice decisions of firms and consumers, CIMS incorporates heterogeneous costs by putting a probability distribution around the life-cycle cost of a technology, with the engineering estimate as the average cost and the "v" parameter representing the variability of costs. As discussed in Section 3.1, if market data shows high variability in the technology choices for a given energy service, then “v” will be small, and vice versa if the market for an energy service is fairly uniform.

The second category of intangible costs is risk of technology failure or malfunction. New technologies usually have a higher chance of premature failure because they are not “tried, tested, and true”. Conventional technologies such as the combustion engine and steam turbine have been utilized for over a century. Incremental innovations to these technologies have made them dependable and society has amassed considerable knowledge on how to run and repair them. As well, technology risk can be higher in new technologies with lower emission or higher energy efficiency because these technologies usually have higher upfront capital costs, meaning they will have longer payback periods. Since the cumulative probability of failure or accident or undesired economic conditions increases over time, any technology with a longer payback period is riskier by nature (Jaccard, 2005b). The risk of longer payback periods is why many firms require a payback period for investments of 2-3 years, equivalent to annualizing capital costs with a discount rate of 33-50% (Nyboer, 1997).

The third category of intangible cost is loss of option value. Option value is the value of delaying an irreversible investment, which gives an investor an opportunity to wait for new information about prices, costs, and overall market conditions. The conventional rule for when to make an investment is to invest when the net present value of a unit of capital is at least as large as its purchase and installation cost. Pindyck (1991) explains that this rule does not explain investment behaviour for irreversible and avoidable investment decisions. He modifies the conventional rule to “the value of the unit of capital must exceed the purchase and installation cost by an amount equal to the value of keeping the investment option alive.”

Risk and option value overlap to the extent that a firm or consumer will value waiting to invest in a new technology until they can receive more information about its performance. Because of this overlap and the difficulty in measuring risk and option value for individual technologies, these costs are represented by the revealed discount rates that research shows firms and consumers use to amortize capital costs in particular sectors or for particular energy services. Revealed discount rates are typically higher than standard financial discount rates. For example, some firms demand a 2-year payback for capital investments and will thus annualize capital costs with a discount rate of 50%. Consumers have also been found to have high discount rates for more energy efficient technology. Despite the fact that engineering cost estimates suggest consumers would save money by adopting these technologies, adoption rates are quite low.

The fourth component of intangible costs is loss of consumers' surplus, which is the extra value that consumers receive above the financial cost of a particular technology. The significance of consumer surplus is that even though one technology may have the lowest financial cost for delivering an energy service, another technology may provide a larger consumer surplus. All technologies have different attributes and associated risks, meaning varying degrees of technology "substitutability" exist for any given energy service. For example, while small cars may cost less to operate per kilometer, many consumers value sports-utility vehicles and pick-up trucks for their comfort, utility, safety, and even cultural status. Consumers also value the convenience of owning a car over public transit, even though transit is a considerably cheaper mode of transportation (Jaccard et al., 2004).

Consumers' surplus is simulated in CIMS at two levels – the energy service level and the technology level. Energy services refer to the aggregate demand for a service such as mobility or square feet of housing. In the CIMS residential and personal transportation sectors, the demand for these services changes according to a price elasticity parameter, which will decrease demand if the price of consuming the service increases. The loss of demand for an energy service represents a consumers' surplus loss.

At the technology level, consumers' surplus is represented in a parameter called "intangible costs", which is used in the calculation of life cycle costs for technologies that are known to have considerable non-financial values for firms and consumers. This parameter will raise the costs of less preferred technologies and decrease the costs of preferred technologies. The most rigorous way to determine this parameter is through revealed choice data and stated preference choice surveys, as was done for personal vehicle choices in Axsen *et al.* (2009). In the absence of such studies, CIMS modelers will use this parameter to calibrate observed technology choices as shown through market data.

The last component of intangible costs can actually be thought of as a “false cost”, or a portion of the perceived cost that does not actually result in a real cost on the firm or consumer. Discussed further in the upcoming section on Expected Resource Cost, these false perceived costs occur due to the market failures of lack of information and bounded rationality.

The following sections explain how the different components of cost explained above are combined to form CIMS’ three different methods of calculating cost. The first method, *techno-economic cost* (TEC), can be considered a lower bound estimate of cost and is consistent with a definition of cost employed by bottom-up models. The second method, the *perceived private cost* (PPC) is an upper bound estimate of cost, consistent with the economic theory employed by top-down models. And lastly, the *expected resource cost* (ERC) is a measure between the TEC and the PPC, which the Energy and Materials Research Group thinks most closely estimates the real cost of a policy to society. Refer back to Figure 2 (pg. 31) for a depiction of the components of cost included in each of these measures.

Techno-Economic Cost

The techno-economic cost (TEC) measure represents just the *ex ante* engineering estimates of capital, operating, and energy costs – depicted in the far left hand side of Figure 2. No components of intangible cost are included in the TEC measure. Techno-economic cost of a policy is calculated from the output of a CIMS simulation by taking the difference in total investment on capital, energy and operating & maintenance between the policy scenario and the business as usual scenario. Equation 5 shows how TEC is calculated for each period in a scenario. Investment on capital refers to the full upfront capital investment – for example, if a power plant is built in 2014 at a total capital cost of $40 million and it will operate for thirty years, the investment cost of this plant will count as $40 million in the period 2011-2015 and will not be annualized over later periods. The capital cost factor and annual cost factor discount the values to the first year in the period.

***Equation 5	Techno-Economic Cost Equation for CIMS***

$$TEC_{5\,Year\,Period} = \left(Investment_{5\,year\,period} * Capital\ Cost\ Factor\right) + \left(O\&M_{Annual} + Energy_{Annual}\right) * Annual\ Cost\ Factor$$

Discount Rate = 5%
Factor = 1 + discount rate = 1.05
Annual Cost Factor = (factor^4 + factor^3 + factor^2 + factor + 1)/factor^5 = 4.33
Capital Cost Factor = Annual Cost Factor / 5 = 0.87

Following the calculation of TEC using Equation 5 for each period in the simulation (2001-2050), the TEC values are discounted to present value in year 2012 using a 5% discount rate. A discount rate accounts for the fact that an opportunity cost exists for the investment of capital and that people generally perceive a future cost as lower than a present day cost. In other words, people perceive a future cost of $100 as less valuable than paying $100 today. Determining just how much lower keeps many economists busy. For policies that will mainly affect private consumption (as opposed to public expenditure), discount rates are typically determined by estimating the social opportunity cost of capital or the real rate of return on capital (Ward, 2006). When the economy is growing fast, the discount rate is higher because the rate of return on capital investment is high. In the 1990s, when the US economy was growing faster compared to present times, discount rates used by the US government typically ranged from 7-10% (Morrison, 1998). Post 2008-2009 recession, a discount rate between 3-7% is more typically applied (EIA, 2009; EPA&NHTSA, 2011b). The specific discount rate of 5% was chosen because this is the rate that the US Energy Information Administration recently used in estimating the cost of a clean electricity policy (EIA, 2010).

Perceived Private Cost

TEC is our best estimate of the known and average financial costs of mitigation, but it underestimates the cost of a policy because factors such as heterogeneity, risk, option value and consumer/firm preferences are not taken into account. The perceived private cost (PPC) measure was developed to incorporate these factors. The term “perceived private” cost refers to the estimate of costs as they would be *perceived* by individuals and firms. As discussed further in the following paragraphs, *perceived* does not necessarily mean real *ex poste costs.* PPC is the total sum of all the costs depicted in Figure 2: engineering estimates, heterogeneity, risk, option value, consumers' surplus, and false perceived costs due to market failures. PPC can be thought of as similar to the welfare cost estimates of top-down models, which also assume that all deviations from the BAU scenario will incur a cost.

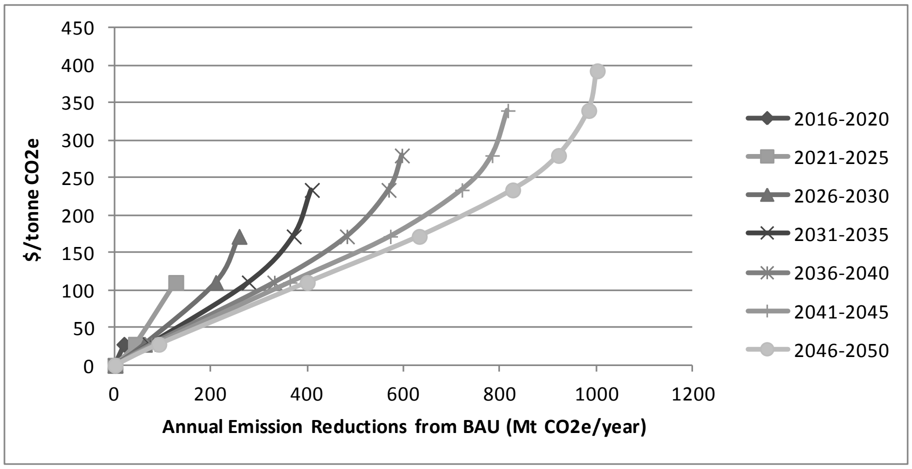
This method measures the perceived costs of a regulation through adding a "shadow price" on emissions or fuel consumption in the market share algorithm of CIMS (Equation 1 and Equation 2, pg. 26) for the technologies or energy services covered by a policy. This shadow price is adjusted until the policy objective is achieved. By restricting or expanding the set of technologies with a shadow price, policies can be modelled in varying scales from economy-wide, to sector-wide, to technology-specific. For example, if the policy objective is a technology regulation to phase out coal generation, a shadow price on the emissions from coal generation technologies would be set to effectively price coal generation out of the market. Or if the policy is a sector-wide performance standard to achieve a certain emissions intensity of production, a shadow price on all GHG emissions in that sector would be applied to reach the specific performance standard.

As policies become more stringent through time, the shadow price increases. For example, a clean electricity standard mandating 20% clean generation in 2015 will require a relatively low shadow price, and then as the target increases to say 80% clean generation in 2040, the shadow price will be quite high.

Shadow prices represent the implicit marginal cost of achieving an objective with a particular policy. They can be used to construct a marginal abatement cost curve for a policy, which shows the amount of emissions reduced as a function of shadow price and time. The perceived private cost of a policy is then calculated by finding the area under the marginal abatement cost curve for each time period. Marginal abatement curves can also be used to calculate the PPC for energy efficiency policies by finding the amount of energy conserved from a shadow price on energy consumption. See Appendix 2 for an example calculation of PPC.

Time is an important factor when plotting marginal abatement curves because an emission price of $10 will result in increasingly higher annual emission reductions the longer it is in place. For example, a $10/t CO_2e emission price in 2015 may only result in a 50 Mt CO2e annual emission reduction, but by 2030, the same $10/t CO2e emission price may have reduced annual emissions by 200 Mt CO_2e. The increasing impact of an emission price is a result of technology turnover. As time goes by, more technologies reach their end life and need to be replaced, thus increasing the influence an emission price has on the acquisition of new, lower emission, technologies. Figure 3 shows marginal abatement curves estimated by CIMS-US for a price on emissions in the personal vehicles sector. Note how an emission price of $240/tonne results in greater emission reductions in later simulation periods.

Figure 3 Example - Marginal Abatement Curves for Personal Vehicle Sector



The PPC method is underpinned by the classical economic assumption that consumers and firms are best informed about their true costs and thus the business as usual scenario represents their “least costly” path forward. Any policy that forces consumers and firms to deviate from the business as usual would then automatically incur additional costs on society. While the TEC measure can find a policy that will produce savings for society, the PPC measure will never find a policy to result in cost savings.

The area under the marginal abatement cost curve represents what businesses and consumers "perceive" to be their cost of reducing emissions. However, their perceptions can be incorrect if market failures exist that obscure their perceptions of cost.

Jaffe & Stavins (1994) describe two market failures that affect adoption rates of energy-saving technologies: (1) lack of information, and (2) principal-agent problems (ex: landlord/tenant). If present, these market failures make consumers and firms perceive energy-saving technologies as more expensive, and thus increase the observed discount rate for technology investments. However, high revealed discount rates could also exist because consumers just truly have high discount rates for irreversible investments with uncertain paybacks. For example, future energy prices are uncertain and life-cycle energy savings can only be estimated (Hassett & Metcalf, 1993).

Thus high revealed discount rates for any particular technology will be caused by some combination of market failure and uncertain paybacks. Separating the two influences requires well structured studies that are few and far between. Knowing the cause of high discount rates is not crucial for the simulation of technology choices – just having an estimate of revealed discount rates will enable more accurate simulation of behaviour. But when the objective is to calculate the total cost of a policy after a simulation, the cause of high discount rates becomes relevant. If revealed discount rates are artificially inflated by the presence of market failures, they are including false perceived costs. When included in a calculation of total cost, these false costs overestimate the real cost of a policy.

While the common default assumption among economists is that consumers make optimal choices and thus revealed discount rates accurately represent private costs of an investment. An increasing number of research studies from the field of behavioural economics show that consumers often do not make optimal choices due to the presence of market failures. For example, a research study by Moxnes (2004) indicates that a regulation to increase the energy efficiency of refrigerators would increase welfare on average for consumers because enough consumers were making non-optimal choices on account of information processing costs and lack of information on the energy efficiency of refrigerators. As well, Thaler & Sunstein's book *Nudge* (2008) details case after case where information processing costs lead to non-optimal choices. Thaler and Sunstein then argue for companies and governments to adopt a philosophy of "liberal paternalism" to carefully set the default choice in various arenas to minimize information processing costs and increase welfare of individuals and society.

Since the perceived private cost method includes revealed discount rates, there is reason to believe that this method will overestimate the total cost of a policy. However, to reduce revealed discount rates for technologies to account for the presence of market failures would require a study equivalent to Moxnes (2004) for every technology in CIMS. Since resources do not allow for this level of empirical rigour, the Energy and Materials Research Group (EMRG) at SFU developed a short-cut technique: the *Expected Resource Cost (ERC)*. The ERC is set to 75% of the distance between the TEC and the PPC (Equation 6). The ERC thus assumes that 25% of the additional perceived cost of PPC compared to TEC is due to market failures and thus does not represent a real cost of implementing a policy (Murphy *et al.*, 2007).

Equation 6 Expected Resource Cost

$$\boldsymbol{ERC = TEC + [0.75 * (PPC - TEC)]}$$

The level of 75% was chosen because the EMRG group did not think that market failures would account for more than half the difference between TEC and PPC and thus chose 75% as a conservative estimate. One could critique the choice of 75% insofar as it is based on judgement and not direct empirical analysis, and this could be reason to revisit the method in the future. Indeed Peters (2006) developed an alternative calculation method for ERC whereby an analyst can take the output from a CIMS simulation and then apply modified discount rates, intangible costs, and heterogeneity parameters that reflect the *ex poste* costs of technology switching as opposed to the perceived costs. However, for this method to be better than the conventional method, it requires empirical estimates of these parameters. For most technology choices, these parameters have not been estimated, thus for the purposes of this study, I chose to remain with the traditional method for calculating ERC.

4. Calibration & Model Settings of CIMS-US

CIMS has developed over the last two decades in the Energy and Materials Research Group at Simon Fraser University. The model originated as discrete technology-specific sectoral models developed by the Pacific Northwest National Laboratory. These “ISTUM sub-models” were given to EMRG and adapted to represent Canada by Mark Jaccard and John Nyboer (Nyboer, 1997). The Ph.D. research of Chris Bataille took the ISTUM sub-models and integrated them into one model with macro-economic feedbacks, CIMS-Canada (Bataille, 2005).

The Master’s research of Bill Tubbs modified the CIMS-Canada model to make CIMS-US (Tubbs, 2008). CIMS-US has then been updated since by Suzanne Goldberg, Mike Wolinetz, Jotham Peters, Adam Baylin-Stern and myself for use in Stanford University’s Energy Modeling Forum 24 in 2011. The Energy Information Administration’s Annual Energy Review (historical data) and Annual Energy Outlook (forecast) are used to calibrate CIMS-US.

This chapter gives an overview of how CIMS-US compares to EIA’s historical data on primary energy consumption and GHG emissions. The calibration of the electricity sector and personal transportation sector is examined in more detail, as the policies in this study are focused on these sectors.

4.1. Economy-wide

Table 1 compares total primary fossil fuel consumption for CIMS against the Annual Energy Review for years 2000 and 2010 (EIA, 2011a). Primary coal consumption in CIMS is within a 3% and 1% range of AER in periods 2001-2005 and 2006-2010, respectively. Natural gas consumption is within 7% and 0% range of AER in periods 2001-2005 and 2006-2010. CIMS primary petroleum consumption is considerably lower because AER includes petroleum feedstocks as part of primary energy consumption.

Table 1 ***Fossil Fuel Consumption*****, Economy-wide**
Average PJ/year for 5-year period

Calibration Results for CIMS-US (Average PJ/year in period)

	Coal		Natural Gas		Petroleum	
	2001-2005	**2006-2010**	**2001-2005**	**2006-2010**	**2001-2005**	**2006-2010**
Annual Energy Review (2010)	23,507	22,808	24,189	24,846	35,904	34,813
CIMS	24,284	22,611	22,449	24,918	33,492	31,601
% Difference	3%	-1%	-7%	0%	-7%	-9%

Table 2 compares CO_2 emissions in CIMS with historical data from the Annual Energy Review. For the five year periods ending in 2005 and 2010, CIMS is within 2% and 3% of historical data, respectively.

Table 2 **CO_2 Emissions from Energy Consumption**
Average Mt CO_2/year for 5-year period

	2001-2005	**2006-2010**
Annual Energy Review (2010)	5,879	5,767
CIMS	5,755	5,614
% Difference	-2%	-3%

4.2. Electricity Sector

Table 3 presents a comparison of electricity generation in the CIMS business as usual scenario with historical and forecasted electricity generation. The reference for years 2000-2010 is historical data from the Annual Energy Review 2010 (EIA, 2011a). The reference for years 2015-2035 is the forecasted generation by the Annual Energy Outlook 2011(EIA, 2011b).

For the most part, CIMS is well calibrated from years 2000-2015 across the different types of generation fuels. For instance, CIMS forecast for coal and nuclear generation in 2015 is within a 1% difference of the reference, and natural gas generation in CIMS for 2015 is about 7% higher than the AEO reference. However, from 2020-2035, CIMS forecasts begin to diverge from AEO 2011. CIMS forecasts that natural gas generation will replace coal generation, leading to a dramatic increase in total natural gas generation. In contrast, AEO 2011 forecasts coal generation will remain constant and natural gas generation will experience a more moderate increase. A factor contributing to the divergence is that CIMS forecasts a 25% increase in total generation between 2020 and 2035, and AEO 2011 forecasts an increase of only 7% during the same time period.

Table 3 **Electricity Generation by Fuel Type (Billion kWh)**
CIMS vs. AER (2000-2010) and AEO 2011 (2015-2035)

	Generation Fuel	Model	2000	2010	2015	2020	2025	2030	2035
Fossil Fuels	**Coal**	Reference	1,911	1,868	1,822	1,825	1,825	1,825	1,827
		CIMS	1,934	1,968	1,808	1,657	1,536	1,434	1,319
		% Difference	1%	5%	-1%	-9%	-16%	-21%	-28%
	Natural Gas	Reference	399	776	917	916	943	1054	1157
		CIMS	399	689	982	1,322	1,708	2,118	2,654
		% Difference	0%	-11%	7%	44%	81%	101%	129%
	Other Fossil Fuel	Reference	98	43	37	38	41	43	48
		CIMS	105	84	72	61	51	40	44
Nuclear		Reference	754	801	833	871	871	871	871
		CIMS	750	841	845	849	853	855	859
		% Difference	0%	5%	1%	-3%	-2%	-2%	-1%
Renewables	**Conventional Hydro**	Reference	271	262	293	301	305	308	311
		CIMS	258	258	258	257	257	257	257
	Biomass	Reference	7	9	11	21	39	38	31
		CIMS	9	10	9	9	8	9	12
	Geothermal	Reference	14	15	20	25	31	42	49
		CIMS	14	20	21	23	26	31	38
	Solar	Reference	0.49	0.83	2.85	3.08	3.36	3.66	3.97
		CIMS	0.49	0.41	0.37	0.34	0.34	0.64	2.84
	Wind	Reference	6	57	143	143	151	157	161
		CIMS	6	23	24	27	32	40	53
Total Generation		Reference	3,473	3,767	4,103	4,175	4,225	4,350	4,475
		CIMS	3,481	3,900	4,028	4,213	4,481	4,796	5,251
		% Difference	0%	4%	-2%	1%	6%	10%	17%

The version of CIMS-US used for this study was calibrated using demand drivers from AEO 2011. CIMS level of total generation is calibrated to reference levels from 2000-2020, but then diverges from reference despite having the same economic drivers. This pattern suggests that the model used to generate the AEO 2011 forecast, NEMS, may be more optimistic that energy efficiency will increase into the future. If anything, this makes the CIMS business as usual scenario more conservative than the reference scenario of AEO 2011.

While differences in total generation levels explains some of the diverging forecasts in natural gas generation and coal generation, it does not explain all of it. The version of CIMS used in this study has equivalent capital, operating, and fuel costs for coal and natural gas generation as AEO 2011, so differences in costs of these technologies is not a reason for diverging trends. One possible reason could be that NEMS has a longer life for coal plants than CIMS. Coal plants can often last longer than their official timeline, especially since considerable opposition exists to building new coal plants. Another possible reason is that EIA experiences political pressure to not show a rapid decline of coal. Consequently, EIA may constrain their model to achieve constant coal generation. Yet another reason could be that the electricity sector in EIA's model has 22 regions, and is thus considering more regional factors than CIMS-US, which is only one region. Examining this issue further was not within the scope of this project, but would be good to look into for future updates of CIMS-US.

Cost of Generation

For the purposes of this report, levelized cost of generation for each technology, *t,* is defined in Equation 7, and is the sum of annualized capital, operating and energy costs, divided by total annual output.

Equation 7 **Levelized Cost of Generation ($/MWh)**

$$Levelized\ Cost\ of\ Generation_t = \frac{CC_t * CRF + OC_t + EC_t}{Output_t}$$

CC_t – Capital Cost of Generation Plant

CRF- Capital Recovery Factor with discount rate of 12.5%

OC_t – Operating Cost of Generation Plant

EC_t – Energy Cost of Generation Plant

$Output_t$ – Output of Generation Plant

Table 4 shows the levelized costs of electricity generation in CIMS for year 2010 compared with the costs used in the NEMS model for AEO 2011(EIA, 2011b).

These levelized costs are the base costs in CIMS and thus they will change according to changes in fuel prices and capital costs. Coal, natural gas, nuclear, biomass, and geothermal generation costs in CIMS are based off of the NEMS costs, thus they have a 0% difference. Wind and solar generation technologies are based on cost curves from the National Renewable Energy Laboratory. While Solar PV is substantially higher than EIA in year 2010, the cost of PV in CIMS decreases with its increased installation. CCS costs for CIMS-US are currently being updated, so updated costs could not be included in this study.

Table 4 Levelized Cost of Generation in 2010 ($US2010/MWh)

	CIMS	**EIA (2011)***	**% Difference**
Pulverized Coal	81.1	81.1	0%
PC with CCS	148.2	131.0	13%
Integrated Coal Gasification Combined Cycle	93.5	93.5	0%
IGCC with CCS	109.5	130.7	-16%
Natural Gas Combined Cycle	56.7	56.7	0%
NGCC with CCS	117.9	85.8	37%
Natural Gas Single Cycle	123.7	123.7	0%
Nuclear	105.4	105.4	0%
Biomass	122.0	122.0	0%
Geothermal	106.9	106.9	0%
Large Hydro	56.1	87.6	-36%
Small Hydro	112.4	0.0	-
Wind	113.9	114.8	-1%
Solar Thermal	242.9	423.7	-43%
Solar PV	429.9	287.2	50%

*The EIA (2011) levelized costs in this table use capital and operating costs from EIA (2010), but use energy costs and discount rate (12.5%) from CIMS to facilitate comparison.

Cost Dynamics

Estimating future generation costs for new renewable technologies and carbon capture and storage (CCS) is complex because both upward and downward cost pressures are at work. As discussed in Section 3.1, most new technologies experience declining capital costs as their production increases. The nature of renewable generation and CCS means these technologies are likely to also face upward cost pressures as their total stock increases.

The first upward cost pressure is related to the site-specific nature of renewable and CCS generation. Whereas natural gas, coal, and nuclear plants can be constructed anywhere, renewable generation must be constructed where the resource is, i.e. where the wind blows or the water flows. CCS is also site-limited, requiring construction near storage reservoirs or near a CO_2 pipeline to a reservoir. The most favourable of these sites are developed first, and then development moves on to less favourable, higher cost sites. A site is more favourable the stronger the resource, the easier it is to access, and the closer it is to where the power will be used.

A second upward cost pressure is related to the low energy density of renewables, which means that renewable generation is more land-intensive than conventional types of generation. As renewable generation expands, it will increasingly face competition by alternative land uses (Green, 2000; Jaccard, 2005b). For instance increasing numbers of proposals for solar thermal generation in California are running up against challenges for these plants to receive adequate water rights for cooling purposes (Woody, 2009). According to a database managed by the US Chamber of Commerce, in March 2010, 149 renewable energy projects in the US were stalled, delayed or blocked by a combination of protracted regulatory reviews, local opposition, and lawsuits (Harder, 2012).

Wind generation is generally thought to experience the greatest variability in the quality of its resource compared to other renewable generation technologies. Accessible sites with strong and stable wind patterns are limited. These good sites are used first and then expanding wind generation means moving into inferior sites with a less stable wind resource. For these reasons, CIMS includes an increasing cost dynamic on wind generation. With increased use of wind generation, capital costs of wind turbines decline, but the cost of siting a wind farm increases. When these two dynamics are put together, wind generation has a slight decrease in levelized costs as production increases, thus the influence of declining capital costs is stronger than the increasing siting costs. Table 5 shows the net effect on the levelized cost of wind for a scenario where wind generation increases 20 times 2010 levels by 2050.

The two solar generation technologies in CIMS, solar photovoltaics (PV) and solar thermal, are only subject to a declining capital cost function. An increasing capital cost function is not included since the quality of the solar resource is more dependable than wind. Table 5 shows that by 2035 the levelized cost of solar PV and solar thermal can decline more than 50% from their 2010 levels in a CIMS simulation. But this level of cost decline will not be the case in every CIMS simulation – declining capital costs of solar depend on their cumulative production as determined by the economic and policy drivers within a CIMS scenario.

Table 5 Declining Solar and Wind Generation Costs in CIMS Reference Case

		2010	2020	2030	2040	2050
Solar Thermal	Total Stock (TWh)	0.00	0.05	1.39	19	45
	Levelized Cost ($US2010/Mwh)	243	177	130	108	108
Solar PV	Total Stock (TWh)	0.41	0.33	0.26	0.63	7
	Levelized Cost ($US2010/Mwh)	430	303	215	154	124
Wind	Total Stock (TWh)	20	91	192	307	399
	Levelized Cost ($US2010/Mwh)	114	111	108	108	108

Nuclear Generation

Without a price on carbon, the levelized price of nuclear generation is higher than coal and natural gas. However, when climate change policy is implemented, nuclear generation quickly becomes the cheapest and most reliable alternative to fossil fuel generation. If CIMS based the choice of new generation technology purely on levelized costs, nuclear generation would increase substantially under a climate change policy. However, levelized cost of generation is only one component in the decision to build a nuclear power plant. Perceptions of risk, both investment risk and safety risk, often drive decisions around nuclear power. Joskow (2006) explains that the numerous problems that arose in building the current fleet of nuclear reactors continues to shape business perceptions around this technology. These problems include lengthy licensing processes, large construction cost overruns, long construction periods, high operation and maintenance costs, the need for early replacement of steam generators and other major pieces of equipment, and public opposition to construction in several regions in the country. In addition, a long-term plan for the disposal of nuclear waste does not exist. For these reasons, no new nuclear plants started construction between 1979, when there was an accident at the Three Mile Island nuclear plant, and 2007.

That said, as of 2012, construction has begun on five new nuclear generation units at three sites (Nuclear Energy Institute, 2012) and the current federal administration is supportive of increasing nuclear generation. In December 2011, the Department of Energy Secretary Steven Chu stated “The Administration and the Energy

Department are committed to restarting America's nuclear industry – creating thousands of jobs in the years ahead and powering our nation's homes and businesses with domestic, low-carbon energy." The Nuclear Regulatory Commission also certified a new nuclear reactor design, Westinghouse Electric's AP1000, and the federal administration committed an $8.33 billion conditional loan guarantee for construction of two of these reactors in Georgia (Brown, 2012). Reflecting the more positive political environment for nuclear power, the Energy Information Administration's Annual Energy Outlook projects nuclear generation will increase from 101.5 gigawatts in 2009 to 110.5 gigawatts in 2035 for their reference scenario. They also have a scenario where an economy-wide GHG price is applied and in this case, nuclear generation increases by 29 gigawatts from 2010-2035, or about 230 TWh/year.

For this study, a new market share limit of 20% is placed on nuclear generation, meaning in any given CIMS period when generation technologies compete to supply new demands for electricity, nuclear can only win 20% of the new demands for generation technology. In the policy scenarios, nuclear generation supplies up to 21% of total generation in 2015 to 30% of total generation in 2050, which works out to an additional generation above 2015 levels of 1,050 TWh/year by 2050. This level of nuclear generation is higher than the AEO forecasts under a climate change policy, but the electricity policies in this study are much more ambitious – achieving 80% zero-emission generation by 2050.

Intermittent Renewable Generation and Storage Costs

The typical approach to comparing generation technologies is through life-cycle production costs per unit of electricity supplied. Indeed, CIMS uses this levelized cost approach. Joskow (2011) criticizes the levelized cost method as misleading when comparisons are made between intermittent (wind and solar) and dispatchable (natural gas, coal, nuclear, biomass) generation technologies. The method is flawed, states Joskow, because it treats all MWhs supplied as a homogeneous product governed by one price, when in reality, the value of electricity (wholesale market price) varies over the day and over the year. For example, the difference between high and low prices over a typical year can be up to four orders of magnitude.

In response to this valid critique, I added a storage cost to the intermittent renewable generation technologies to represent the cost of storing intermittent power. The logic being that storing intermittent power makes it more comparable to dispatchable power. Jaccard (2005b) states that the added cost of energy storage is estimated to be about 1-2 ¢/kWh. Since I am trying to represent a conservative cost estimate, I added a 2¢/kWh storage cost to all intermittent generation technologies. However, this may actually be an optimistic estimate of storage costs, as more recent research estimates the cost is 5¢/kWh ($US2006) and above (Poonpun and Jewell, 2008).

4.3. Transportation Sector

For the transportation sector, Table 6 shows how CIMS fuel consumption in the business as usual scenario compares to reference values, which include the freight and personal transportation sectors. The reference values for years 2005 and 2010 are historical data from the Annual Energy Review 2010 (EIA, 2011a). The reference values for 2015 onwards are from the Annual Energy Outlook (EIA, 2011b). Petroleum and total fuel consumption in most years is within a 3% difference of reference values. Similar to the electricity sector, CIMS forecasts fuel switching to natural gas in the transportation sector and AEO 2011 does not. All of this fuel switching to natural gas is occurring in the CIMS freight transportation sector, not in personal transportation.

Table 6 Transportation Fuel, CIMS vs. AER 2010 and AEO 2011

Transportation Fuel, CIMS vs. AER 2010 (2005-2010) and AEO 2011 (2015-2035)

		AER 2010		AEO 2011				
Transportation Fuel (PJ)		**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**
Petroleum	Reference	28,812	27,058	29,278	29,415	29,362	30,080	31,293
	CIMS	28,688	27,627	28,424	29,499	29,911	29,676	29,608
	% Difference	0%	2%	-3%	0%	2%	-1%	-5%
Natural Gas	Reference	2	8	42	74	106	148	169
	CIMS	6	3	27	118	497	2,125	3,823
E85	Reference	-	-	11	338	981	1,245	1,298
	CIMS	4	6	24	48	103	149	178
Electricity	Reference	27	28	32	42	53	63	74
	CIMS	90	94	107	120	138	156	176
Total	Reference	28,849	27,177	29,362	29,869	30,512	31,536	32,844
	CIMS	28,789	27,749	28,631	29,856	30,749	32,214	33,911
	% Difference	0%	2%	-2%	0%	1%	2%	3%
% Petroleum of Total Fuel	Reference	99.9%	99.6%	99.7%	98.5%	96.2%	95.4%	95.3%
	CIMS	99.6%	99.6%	99.3%	98.8%	97.3%	92.1%	87.3%

Refined petroleum is the dominant fuel in this sector. As shown at the bottom of Table 6, the AER 2010 states that petroleum consumption is over 99% of total energy consumption for 2005 and 2010. AEO 2011 forecasts a slight decrease in petroleum consumption as a percentage of total over 20 years – from 99.7% in 2015 to 95% in 2035. CIMS forecasts a greater decrease in petroleum consumption as a percentage of total consumption as a result of more fuel switching from petroleum to natural gas – from 97% in 2015 to 88% in 2035.

For the business as usual scenario of personal vehicle technologies, AEO 2011 is more optimistic about the uptake of alternatives to the internal combustion engine (ICE) than CIMS-US. Table 7 compares the market share of personal vehicle engines in CIMS-US to AEO 2011. This table gives two values for CIMS-US, one is the market share when intangible costs are included on the new engine technologies (hybrid, electric, etc), and the other is the CIMS-US market share when the intangible costs are removed. The CIMS-US used in this study includes the intangible costs on the engines. With these intangible costs, CIMS forecasts the market share of gasoline engines to be 99% in 2015, decreasing to 93% in 2035. AEO 2011 forecasts gasoline engines to be 86% in 2015, decreasing to 70% in 2035. Part of this discrepancy is that CIMS only counts E85 vehicles that are actually fueled with E85 fuel. AEO 2011 counts all E85 capable vehicles on the road, whether or not they use E85 fuel.

Car companies have an incentive to produce E85 vehicles because they help in meeting the federal corporate average fuel economy standard. When calculating the fuel economy of E85 vehicles, the government currently only includes the 15% of the fuel that is gasoline. However, E85 vehicles can be fueled with E85 fuel or standard gasoline, and consumers have a cost incentive to prefer gasoline over E85 fuel. Nationally, E85 fuel is about 15% lower in price per gallon than gasoline (e85prices.com, 2012). However, E85 has 28% less energy content than gasoline. Additionally, E85 availability is considerably lower than gasoline, with only 1,950 outlets offering E85 fuel in 2009 compared to 121,446 total gasoline outlets across the US (Lane, 2011).

One way to estimate the level of E85 fuel used by E85 vehicles is to compare the market share of E85 fuel to the market share of E85 vehicles within the total vehicle fleet. The EIA (2011c) estimates that consumption of E85 fuel represented 0.004% of total vehicle fuel consumption, while a conservative estimate of E85 vehicles represented 0.205% of vehicles in use in 2009, or about 500,000 vehicles. This estimate for E85 vehicles in use is likely underestimated by the EIA because they only count E85 vehicles that will likely be using E85 fuels, primarily fleet-operated vehicles. This analysis estimates that only 5% of total E85 vehicles sold are fueled with E85 fuel, thus 95% of these vehicles are thought to be fueled with gasoline. Considering these estimates from EIA(2011), the CIMS forecast of 1% of vehicle travel by E85 vehicles actually fueled with E85 fuel seems to be in the correct vicinity.

Table 7 Total Market Share of Personal Vehicle Engines AEO 2011 vs. CIMS with and without Intangible Costs on Engines

Engine Type		2015	2020	2025	2030	2035	2040	2045	2050
Gasoline ICE	AEO 2011*	86%	80%	75%	72%	70%			
	CIMS - with IC	97%	97%	95%	94%	93%	91%	89%	87%
	CIMS - w/0 IC	95%	95%	93%	82%	69%	56%	43%	39%
Diesel ICE	AEO 2011	2%	3%	3%	4%	4%			
	CIMS - with IC	2%	3%	4%	5%	5%	5%	5%	5%
	CIMS - w/0 IC	4%	4%	5%	5%	4%	3%	3%	2%
Hybrid	AEO 2011	2%	3%	3%	4%	5%			
	CIMS - with IC	0%	0%	0%	0%	1%	3%	5%	6%
	CIMS - w/0 IC	0%	0%	1%	1%	10%	20%	30%	35%
Plug-in Hybrid	AEO 2011	0%	0%	1%	1%	2%			
	CIMS - with IC	0%	0%	0%	0%	0%	0%	1%	1%
	CIMS - w/0 IC	0%	0%	1%	11%	15%	20%	23%	22%
Ethanol (E85) ICE	AEO 2011	10%	14%	17%	18%	19%			
	CIMS - with IC	0%	0%	1%	1%	1%	1%	1%	1%
	CIMS - w/0 IC	1%	1%	1%	1%	1%	1%	1%	0%
Pure electric	AEO 2011	0.1%	0.2%	0.3%	0.5%	0.6%			
	CIMS - with IC	0%	0%	0%	0%	0%	0%	0%	0%
	CIMS - w/0 IC	0%	0%	0%	0%	0%	0%	0%	1%

*Annual Energy Outlook 2011, Reference Case, Table: "Light-Duty Vehicle Miles Traveled by Technology

Another factor contributing to the difference between the CIMS and AEO 2011 forecast in vehicle engine type is that CIMS has considerable intangible costs on new vehicle technologies. These intangible costs were set to prevent hybrid and plug-in hybrid vehicles from getting unrealistic market shares in later periods. Referring back to Table 7, examine the values highlighted by the grey bar for year 2035. With no intangible costs, the market share for hybrids and plug-in hybrids spike to 10% and 15% respectively in this period, well above the AEO 2011 projections for these categories. Intangible costs were added to these vehicle types to bring them below the AEO 2011 forecast, thus ensuring a conservative business as usual projection.

Transportation Mode

For personal transportation, the CIMS energy demand service is person kilometers traveled per year. For urban travel, four different modes of travel compete to supply this service: vehicles with just a driver, high occupancy vehicles, transit, and walking/cycling. When shadow prices are used to simulate a VES and CAFE standard, the shadow price is included in the market share algorithm, making driving a vehicle considerably more expensive vis-à-vis the other urban transportation modes. If the four modes are allowed to compete, substantial mode shifting occurs – such as transit going from 4% to 40% market share. However, the shadow price only represents the perceived cost of forcing a switch in technology, it is not actually paid by someone buying a vehicle, so it should not cause this level of mode shifting to occur.

To address this issue, I fixed the urban transportation modes so that they could not compete with each other. If a VES or CAFE standard was simulated with another method that did not affect the market share algorithm, mode shifting would occur, as consumers are being forced to buy vehicles that they would not otherwise choose to buy due to their high perceived cost. Thus by not allowing mode shifting, the cost of these policies will be higher, and thus this setting makes the cost estimate more conservative.

4.4. General Model Settings

Table 8 lists the CIMS' settings for simulating the business as usual and policy scenarios in this study. The first of these two settings, *Energy Supply & Demand* and *CIMS Macro,* are the two main macro-economic processes than can be turned on and off. The *Energy Supply & Demand* function allows for the supply and price of fuels to reflect changes in their demand. For supply and fuel prices to actually change from their exogenous setting, other fuel-specific settings also have to be activated. For example, balancing the domestic supply of coal is only done if the *Constant Coal Production* setting is turned *off*, otherwise, coal is mined according to its exogenous supply schedule.

Table 8 General Model Settings

CIMS Setting	Setting
Energy Supply & Demand	On
CIMS Macro	On
Energy Trade	Off
Constant Coal Production	Off
Constant Crude Production	Off
Constant Natural Gas Production	Off
Constant RPP Production	On
Coal Endogenous Pricing	Off
Crude Endogenous Pricing	Off
Electricity Endogenous Pricing	On
Natural Gas Endogenous Pricing	Off
RPP Endogenous Pricing	On
Ethanol Endogenous Pricing	On
Biodiesel Endogenous Pricing	On
GHG Precognition	Off
Revenue Recycling	On

Note that for coal, crude, and natural gas, the constant production setting is turned *off,* and for refined petroleum products (RPP), it is turned on. The reasoning behind these settings is that domestically produced coal, crude and natural gas are mostly consumed by the United States. They are not large export commodities. Thus their supply is responsive to domestic climate change policies that decrease the demand for fossil fuels. On the other hand, refined petroleum products could become a large export commodity of the United States if climate change policy reduced demand for these products at home, especially since the United States has a large refining industry. The world demand of RPPs would only decrease if enough other countries also implement climate change policies. Since future climate change policies in other countries are uncertain, especially those of developing countries, I make the conservative assumption that international demand for oil remains at forecasted levels. The implication of this assumption is that reduction in output of RPPs is not an option for reducing emissions in the policy scenarios. GHG emission reductions in the RPP sector will only occur through technology or fuel switching.

For fuel prices to change from their exogenous forecast in CIMS, the *Endogenous Pricing* parameter needs to be turned on. Note that endogenous pricing is turned on only for secondary energy sources, namely, electricity, refined petroleum, ethanol, and biodiesel. Primary energy is set to exogenous pricing. The reason behind these settings is that the price of primary energy sources is set on the world market and thus would only be marginally affected by a climate change policy in the United States. Secondary energy consumed in the United States is also mostly produced in the United States, thus the price of secondary energy sources will be more affected by domestic climate change policy than primary energy sources.

The *CIMS Macro* setting determines whether the output of the energy demand sectors is responsive to changes in the cost of energy services. When the *CIMS Macro* is turned on, output levels of sectors can change in response to a climate change policy. Each demand sector has an exogenous output based on reference growth forecasts, such as the *Annual Energy Outlook.* For example, the residential sector's output is number of households. The Iron & Steel sector's output is tonnes of steel. CIMS only represents the cost of production for this output in relation to the cost of energy services needed for producing a unit of output. Through determining what percentage energy services makes up in the total cost of production, an estimate can be made as to changes in the total cost of production due to a change in energy service cost. CIMS then takes this estimate for the change in total cost of production and applies a price elasticity function to get the change in demand for this output. Under an ambitious climate change policy, the cost of production in most sectors will increase, and thus demand will decrease. The level of decrease in demand depends on the price elasticity of demand for the product.

The last two settings in Table 8, *GHG Precognition* and *Revenue Recycling,* relate to the treatment of emission charges. If *GHG Precognition* is turned on, the GHG emission charges of future periods will be considered within the market share algorithm. For this study, *GHG Precognition* was turned off since most of the policies are not direct emission charges. These policies are simulated in the model as shadow emission or fuel charges, but they are actually regulations or tradable performance standards. For purposes of consistency and ease of simulation, *GHG Precognition* is also set to *off* for the carbon tax policies.

When *Revenue Recycling* is turned on, the revenue raised from emission charges, including shadow emission charges, is returned to the sector from which it was raised. In this way, the payment of emission charges is not included in the cost of production for a sector, and thus output and energy prices are not directly affected by emission charges. However, an indirect effect of emission charges still exists since they influence changes in capital, operating, and fuel expenditure, which in turn impacts cost of production.

5. Results and Discussion

This section presents estimates on the cost of different policy options for reducing GHG emissions in the United States. Using the CIMS-US model described in Sections 3.1 and 4, three sets of policy scenarios were simulated, for a total of ten policy scenarios. The first set of policies relates to the electricity sector, the second to the personal transportation sector and the third set considers the simultaneous implementation of policies in the electricity and transportation sectors.

Within each set, the policies achieve equivalent GHG emission reductions in each period, which is achieved by simulating one of the policies in the set, and then configuring the stringency of the other policies in the set to match the emission reductions of the base policy. Matching GHG emissions of policy scenarios requires running iterative simulations of a policy through CIMS-US until the settings of a policy achieves the required emission reductions.

Recall from Section 3.2 that CIMS enables the calculation of three distinct cost measures for policies – the first measure is the techno-economic cost (TEC) measure, representing the ‘bottom-up’ or engineering costing methodology, and the second measure is the perceived private cost (PPC) measure, representing the ‘top-down’ or economist costing methodology. The PPC measure can be interpreted as an “upper bound” or conservative cost estimate. Most likely, the actual cost of implementing these policies would be lower. The Energy and Materials Research Group’s best estimate of the “true cost” of these policies is the third measure – the expected resource cost (ERC). The ERC adjusts the PPC downwards to account for false perceptions of cost included in the PPC. The ERC is calculated by taking the TEC and adding 75% of the difference between the PPC and the TEC.

Unless otherwise noted, all representation of policy cost in this section is relative to the business as usual (BAU) scenario, and is denominated in $US2010 (including costs represented in text, tables and figures). To enable the comparison of costs over different time periods, costs are discounted to their present value in 2012 using an annual discount rate of 5%. The costs presented in all figures represent the total cost of implementing a policy over a five year period (note the period 2011-2015 is just represented as “2015” and so on). Negative cost numbers can be thought of as savings relative to the BAU scenario. Marginal GHG tax rates are in $US2010 and are not discounted.

Below, results for each set of policies are reported and analysed in turn. Firstly, results are presented on the policy configurations that CIMS-US estimates would achieve equivalent GHG emission reductions. Secondly, the cost of implementing these policies is compared and explained.

5.1. Electricity Policies

This section compares the total cost of two policies that are focused on the electricity sector with each other and against an economy-wide GHG tax. The first policy is a technology performance standard that leads to the phase out of conventional fossil fuel generation (Conv. FF Phase-out). This policy first prohibits oil generation and new coal generation without carbon capture and storage (CCS) after 2015 and then prohibits new natural gas generation without CCS after 2030, thus leading to a phasing out of conventional coal and natural gas from the generation mix. The second policy is a clean electricity standard (CES) that mandates a certain percentage of total generation must be from zero-emission sources. Renewable and nuclear generation, and 90% of fossil fuel generation with CCS is considered to be zero-emission generation. The CES is set to achieve equivalent emission reductions as US1. The third policy is an economy-wide tax on GHG emissions that results in the same level of emission reductions, economy-wide, as the Conv. FF Phase-out and CES policies.

Table 9 outlines the configuration of these policies in greater detail and shows the difference between the BAU scenario and the policy scenario. For the Conv. FF Phase-out, coal generation begins to decrease relative to the BAU after 2015, and natural gas generation decreases after 2030. To match the GHG emission reductions from a phase out of conventional fossil fuel generation, CIMS-US finds that a clean electricity standard needs to be 81% by 2050 and an economy-wide tax needs to be \$124 / tonne CO_2e.

Table 9 Policies – Electricity Sector

Conv. FF Phase-out		**2015**	**2020**	**2030**	**2040**	**2050**
Coal Generation	BAU	1,807	1,656	1,433	1,273	1,404
(TWh/year)	Policy	1,807	1,578	1,097	446	13
Natural Gas Generation	BAU	982	1,321	2,114	3,257	4,226
(TWh/year)	Policy	982	1,401	2,462	1,442	760
CES		**2015**	**2020**	**2030**	**2040**	**2050**
% Clean Electricity	BAU	29%	28%	25%	22%	18%
	Policy	29%	28%	28%	58%	81%
GHG Tax - Match Elec		**2015**	**2020**	**2030**	**2040**	**2050**
\$US2010/tonne CO2e	BAU	0	0	0	0	0
	Policy	0	2	16	121	124

Table 10 Annual Economy-wide GHG Emissions (Gt CO_2e) and % Reduction from 2005 GHG Emissions

	2010	**2020**	**2030**	**2040**	**2050**
BAU	6.4	6.5	6.7	7.2	7.9
	-2%	-1%	2%	9%	21%
Conv. FF Phase-out	6.4	6.5	6.5	5.8	5.6
	-2%	-1%	0%	-12%	-15%
CES	6.4	6.5	6.4	5.8	5.6
	-2%	-1%	-2%	-12%	-15%
GHG Tax - Match Elec	6.4	6.5	6.5	5.8	5.6
	-2%	-1%	-1%	-11%	-15%

As shown in

Table 10, the emission reductions from the CES and GHG tax follow the same path as the phase-out of conventional fossil fuel generation. Each of these policies stabilizes emissions at 2005 levels in 2030, and achieves a 15% reduction in GHG emissions from 2005 levels by 2050. CIMS-US forecasts GHG emissions for the BAU scenario in 2030 as 2% above 2005 emissions, and 2050 emissions are forecasted to be

21% above 2005 levels. Since each policy results in equivalent emission reductions, the economic impact of these policies can be compared.

The total present value (PV) costs of the first set of policies are presented in Table 11. As expected, both the TEC measure and the PPC measure find that the technology regulation of phasing out conventional fossil fuel generation would be the most costly method of reducing GHG emissions. However, the PPC estimates the cost of this policy to be about three times the amount than the TEC measure over the period 2016-2050, thus highlighting the different definitions of “cost” employed by these two measures.

By the TEC, the total cost of the FF phase-out and the CES is relatively similar, but by the PPC, the CES is less than half the cost of the FF phase-out. The difference between the PPC and the TEC is the amount of intangible costs of a policy. While the FF phase-out has about $1 trillion of intangible costs over the simulation period, the CES has just under $300 billion.

The ERC estimates the total PV cost of the phase-out of coal and natural gas generation to be $1,214 billion over the 35 year simulation period, or $35 billion a year on average. The total ERC for the clean electricity standard is estimated to be $598 billion over 35 years, or $17 billion a year on average. The economy-wide GHG tax is estimated to be $314 billion, or $9 billion a year on average. Thus compared to the tax, the technology regulation is estimated to be about 4 times more costly, and the clean electricity standard is found to be about 2 times more costly.

Note that the cost measures for the GHG tax do not represent the revenue generated by the tax and then transferred back to society. This revenue is considered a transfer and not a cost. The TEC cost measure represents the change in expenditure on capital, operating and energy costs under a GHG tax relative to the BAU. The PPC cost measure for the GHG tax is the amount of certain and intangible cost firms and consumers are willing to incur to avoid paying the tax.

Table 11 Total Cost - Electricity Policies

Total Cost of Policy (US$2010 Billions, discounted to 2012 at r = 5%)

Techno-Economic Cost	2016-2050	Annual Average	% Difference from Tax
Conv. FF Phase-out	522	15	235%
CES	384	11	147%
GHG Tax - Match Elec	156	4	0%
Perceived Private Cost	**2016-2050**	**Annual Average**	**% Difference from Tax**
Conv. FF Phase-out	1,445	41	294%
CES	670	19	83%
GHG Tax - Match Elec	367	10	0%
Expected Resource Cost	**2016-2050**	**Annual Average**	**% Difference from Tax**
Conv. FF Phase-out	1,214	35	287%
CES	598	17	91%
GHG Tax - Match Elec	314	9	0%

Figure 4 Total Cost – Electricity Policies

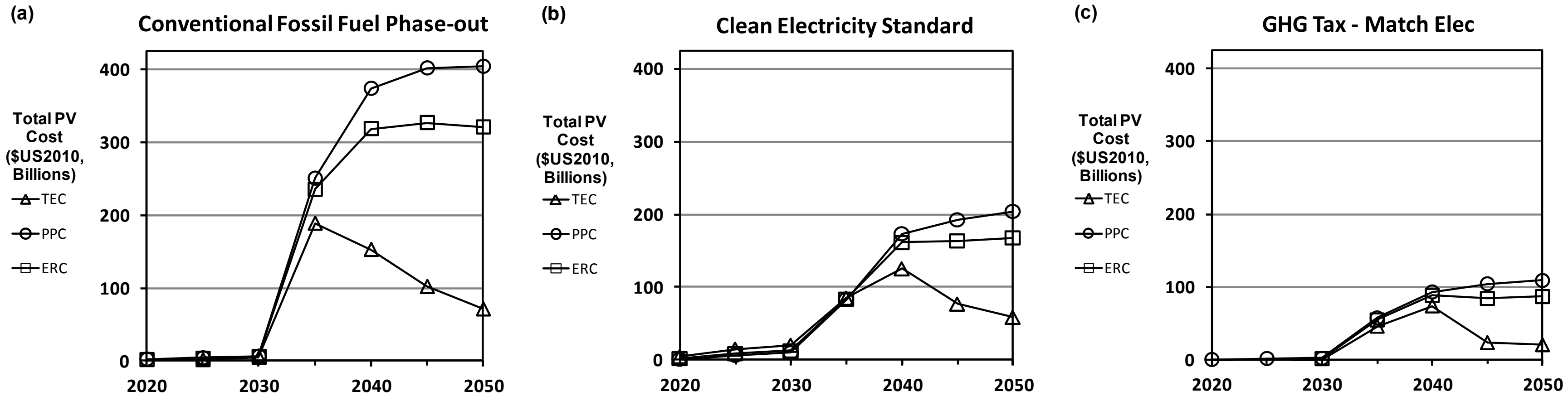


Figure 4 compares the cost measures for each separate policy. For the Conv. FF Phase-out, Figure 4a shows the PPC and TEC measures to be relatively close from 2016-2030, with both measures estimating relatively low costs for the phase-out of conventional coal in this period. These low costs can be explained because most new installations of generation capacity are forecasted to be natural gas combined cycle technology, not coal generation. Thus a phase-out of coal during this period is only forcing a small divergence from the business as usual scenario. The two measures then increase substantially in 2035 as a result of the requirement to phase out natural gas, as this is a significant divergence from the BAU scenario. The two measures also differentiate substantially from 2040-2050, indicating substantial intangible costs during these periods.

While a marked difference exists for the Conv. FF Phase-out between TEC and PPC, Figure 4b shows the two measures have similar estimates of cost for the clean electricity standard. Since the TEC for these two policy scenarios are similar, but the PPC costs are quite different, the conclusion can be drawn that FF Phase-out has substantially more intangible costs than the CES.

Higher intangible costs for the FF Phase-out are likely a function of the CIMS heterogeneity parameter, which accounts for the fact that costs vary from one decision making situation and location to another. Inclusion of this parameter in the market share algorithm means that even if the average cost of a technology is expected to be quite high compared to other substitutes, the technology will still receive a small market share to represent the diversity of situations. The relevance of this for modeling technology phase-out policies within CIMS is that a substantial shadow emissions charge must be placed on a technology to bring its new market share from 1% to 0%, and a higher shadow emissions charge means higher perceived private cost (discussed further in Section 6.2). Furthermore, in 2031, the Cov. FF Phase-out policy demands no new market share of two technologies which formerly made up the majority of market share. In adding a shadow emissions charge to phase out conventional natural gas, I also had to raise the shadow emission charge I placed on conventional coal technologies, demonstrating how the simultaneous phase out of both of these technologies is more costly than just summing up the cost of phasing out both of these technologies independently.

Looking at the generation mix of the electricity policies in Table 12 for the 2050 period, note how the policy to phase-out conventional fossil fuel generation has a 0% market share for coal and the CES still has a 1% market share for coal. Part of the reason the CES has smaller intangible costs is because of the value associated with allowing a small amount of market share of a technology.

Table 12 Generation Mix - Electricity Policies

Conv. FF Phase-out	**2020**	**2030**	**2040**	**2050**	**CES**	**2020**	**2030**	**2040**	**2050**
Fossil Fuels	72%	75%	37%	15%	**Fossil Fuels**	72%	72%	41%	18%
Coal	37%	23%	8%	0%	Coal	38%	24%	6%	1%
Natural Gas	33%	51%	26%	12%	Natural Gas	32%	47%	34%	15%
10% CCS	0%	0%	2%	2%	10% CCS	0%	0%	1%	1%
Other	1%	1%	1%	1%	Other	1%	1%	1%	1%
Zero-Emission	28%	25%	63%	85%	**Zero-Emission**	28%	28%	59%	82%
Nuclear	20%	18%	25%	30%	Nuclear	20%	18%	24%	29%
90% CCS	0%	0%	16%	22%	90% CCS	0%	0%	8%	12%
Hydro	6%	6%	6%	7%	Hydro	6%	6%	6%	7%
Wind	1%	1%	13%	19%	Wind	1%	3%	16%	25%
Solar	0%	0%	2%	5%	Solar	0%	0%	3%	7%
Biomass	0%	0%	0%	1%	Biomass	0%	0%	1%	1%
Geothermal	1%	1%	1%	1%	Geothermal	1%	1%	1%	1%
Total Generation (TWh)	4217	4822	5562	6344	**Total Generation (TWh)**	4213	4778	5592	6407
Emissions Intensity (kt C02e/TWh)	484	403	190	72	**Emissions Intensity** (kt C02e/TWh)	485	388	188	80

The generation mix also indicates other reasons why the phase-out of conventional fossil fuel generation has higher costs than the CES. Compared to the FF phase-out, the CES scenario has a lower percentage zero-emission generation in 2040 and 2050, higher emissions intensity in 2050, and greater total generation in 2040 and 2050. Yet these two scenarios have equivalent GHG emissions at the economy-wide level in 2040 and 2050. This seeming discrepancy can be explained by two factors (1) the difference these two scenarios have over the electricity price, and (2) the increased consumption of CCS under the FF phase-out.

Firstly, electricity price increases under the FF phase-out are higher than the CES after 2031, inducing a greater switch away from electricity consumption to direct natural gas generation in the residential and commercial sectors. For example, space and water heating fueled by electricity can be switched to natural gas. Indeed, this fuel switching results in a 250 PJ increase in natural gas consumption in the energy demand sectors (residential, commercial, and industrial), corresponding to a 13 Mt CO_2e difference in emissions.

The other factor is that the FF phase-out policy results in substantially more CCS generation. While 90% of GHG emissions from CCS *generation* are captured, emissions associated with increased natural gas and coal *extraction* are not captured, resulting in the emissions of 50 Mt CO_2e more from energy supply sectors compared to the CES. The CES has less CCS generation for two reasons: (1) the CES allows for higher natural gas generation from 2030-2050, (2) 10% of CCS generation is not counted as “zero-emission” thus CCS in a CES is at a competitive disadvantage to CCS in the FF technology phase-out.

In summary, since the Conv. FF phase-out policy has greater indirect effects on emissions in other sectors, the CES can achieve the same amount of emission reductions economy-wide with less effort, i.e. smaller % zero-emission generation, and therefore the CES is less costly to implement.

5.2. Personal Transportation Policies

This section compares two personal transportation sector policies: a corporate average fuel economy (CAFE) standard, and a vehicle emissions standard (VES). These policies are intensity based standards applied to the new fleet of cars for a given year, the CAFE sets a standard of MJ of fuel consumed per vehicle kilometre travelled (vkt). The VES sets a standard of tons CO_2e emitted per vehicle kilometre travelled (see Table 13). Every year, a car company’s new fleet of cars needs to meet these standards on average, meaning they can sell cars above the standard as long as they also sell cars below the standard. These standards are also tradable between companies, thus the marginal cost for complying with the standard is assumed to be equal across the sector. These scenarios only examine the effects of personal transportation policies in isolation; the electricity sector operates under business as usual conditions.

The CAFE standard is set to correspond with final standards *approved* by the US President from 2012-2016 and standards *proposed* by the federal administration from 2017-2025. After 2025, the CAFE standard is set on a linear course to achieve a tripling of fuel economy by 2050 from 2005 levels, a policy that was defined and studied in Stanford University’s Energy Modeling Forum 24.

The modeling of the VES in CIMS assumes that all E85 vehicles sold will use E85 fuel. As discussed in Section 4.3, a slight cost incentive exists to fuel E85 vehicles with gasoline. The EPA will be addressing this issue with respect to their VES by taking into account national E85 fuel consumption. The current structure of CIMS does not allow for these dynamics to be included in this study. The significance of not including these dynamics is that CIMS may overestimate the number of E85 vehicles that will be produced by companies to reach the VES.

Table 13 Policies – Personal Transportation

CAFE		**2010**	**2020**	**2030**	**2040**	**2050**
(miles/gallon)	BAU	24	26	27	28	28
	Policy	24	36	51	62	73

VES		**2010**	**2020**	**2030**	**2040**	**2050**
(g CO2 / mile)	BAU	376	327	309	301	301
	Policy	376	243	115	69	43

GHG Tax - Match Trans		**2010**	**2020**	**2030**	**2040**	**2050**
($US2010 / tonne CO2e)	BAU	0	0	0	0	0
	Policy	0	9	57	57	57

The vehicle emissions standard was set to achieve equivalent emission reductions in the personal transportation sector as the CAFE standard (see Table 14). However, since the VES results in greater ethanol production than the CAFE standard, economy-wide emissions for the VES are slightly higher than the CAFE in periods 2025-2045, but reach equivalency in 2050. For comparison, an economy-wide GHG tax is applied that achieves equivalent emission reductions as the direct emission reductions of the CAFE and VES policies within the personal transportation sector. Indirect emissions from electricity generation and ethanol production are not considered in the calculation of the target for the GHG tax.

Table 14 Greenhouse Gas Emissions - Transportation Policies

Greenhouse Gas Emissions (Gt CO2e)		**2010**	**2020**	**2030**	**2040**	**2050**
BAU	Economy-wide	6.4	6.5	6.7	7.2	7.9
	Electricity	2.2	2.1	2.1	2.3	2.7
	Transportation	1.4	1.5	1.6	1.8	2.0
CAFE	Economy-wide	6.4	6.4	6.2	6.6	7.4
	Transportation	1.4	1.4	1.0	0.8	0.6
	Electricity	2.2	2.1	2.2	2.7	3.6
	Ethanol	0.04	0.0	0.1	0.1	0.1
VES	Economy-wide	6.4	6.4	6.4	6.8	7.4
	Transportation	1.4	1.4	1.0	0.8	0.6
	Electricity	2.2	2.1	2.2	2.5	3.1
	Ethanol	0.04	0.1	0.2	0.4	0.5
GHG Tax - Match Trans	Economy-wide	6.4	6.4	6.1	6.0	6.4
	Electricity	2.2	2.1	1.8	1.7	1.8
	Transportation	1.4	1.5	1.5	1.7	1.9

The CIMS personal transportation sector includes all standard modes of personal transportation within cities and between cities. In addition to vehicles, the sector also includes transportation by foot, bicycle, bus, rail, and air. As the CAFE and VES standards become more stringent in later periods, the emissions from vehicles are near zero and the remaining emissions in this sector are from travel by bus, rail and air.

By 2050, both the CAFE and the VES reduce GHG emissions in the personal transportation sector by 1,450 Mt CO_2e from their projected levels under the BAU scenario. However, under both policy scenarios, about 65% of these emission reductions are negated by increased emissions from energy supply sectors, thus the net reduction in economy-wide GHG emissions is only 500 Mt CO_2e from BAU levels in 2050. By comparison, the Copenhagen target aims to be 6800 Mt CO_2e below BAU levels in 2050 at 1100 Mt CO_2e/year.

Under a CAFE policy, GHG emission increases are primarily in the electricity sector – increasing by 800 Mt CO_2e from BAU levels in 2050. As well, GHG emissions in the natural gas extraction sector increase by 100 Mt CO_2e from their BAU levels in 2050 due to increased natural gas demand from the electricity sector. These emission increases are a result of increased total generation by this sector as vehicles switch from being primarily fueled by gasoline to being primarily fueled by electricity. Electric vehicles are the most efficient vehicle option on the market today and a tripling of fuel economy can only be achieved with a high percentage (~70%) of electric vehicles in the fleet.

Since CIMS was set to produce constant levels of refined petroleum products, the decrease in demand of gasoline under a CAFE did not result in decreased gasoline production. Thus under this configuration of CIMS- US, GHG emission increases in the electricity sector were not offset by emission reductions in the petroleum refining sector. In reality, GHG emissions would probably decrease in the petroleum refining sector, but since the status of future export markets for refined petroleum is highly uncertain, production was held constant to produce conservative results for emission reduction potential under these transportation policies.

Under a VES policy, GHG emission increases are split evenly between electricity and ethanol production, with each sector increasing direct emissions by 400 Mt CO_2e from BAU levels in 2050. As well, increased production in both of these sectors increased natural gas demand, resulting in 130 Mt CO_2e increase in the natural gas extraction sector by 2050 from BAU levels. At 50% of new market share, the plug in ethanol vehicle is the most popular vehicle option by 2050, explaining why GHG emission increases occur in both the electricity and ethanol production sectors.

The finding that a CAFE and VES policy result in similar GHG emissions at the economy-wide level is somewhat surprising since total energy consumption under a VES policy is 10,000 peta joules (PJ) higher than under the CAFE policy in 2050. The VES policy scenario can achieve similar overall emission levels while having substantially more energy consumption because the GHG emissions intensity of ethanol production is 30% of the emissions intensity of electricity generation. In 2050, ethanol production emits 0.04 tonnes CO_2e per giga joule (GJ) of ethanol produced, and the electricity sector emits triple this amount at 0.12 tonnes CO_2e per giga joule of delivered electricity.

In 2050, the economy-wide GHG tax policy achieves annual emission reductions of about 1500 Mt CO_2e economy wide from the BAU scenario, which is three times higher than the emission reductions at the economy-wide level of the CAFE and

VES policies, but equivalent to the direct emission reductions within the personal transportation sector under the CAFE and VES. Interestingly, hardly any of the emission reductions under this GHG tax come from the personal transportation sector - 65% of the reductions come from the electricity sector, 7% from the personal transportation sector, and 28% from other sectors.

Table 15 shows the total present value cost of the second set of policies. The TEC measure finds substantial cost savings under a CAFE standard, estimating a $56 billion a year savings over the forty year simulation period. The TEC measure finds the VES to be the most costly policy at $7.6 billion a year, and the GHG tax has a small cost at $1.2 billion a year over the forty year simulation period.

Table 15 Total Cost – Transportation Policies

Total Cost of Policy (US$2010 Billions, discounted to 2012 at r = 5%)

Techno-Economic Cost	**2011-2050**	**Annual Average**	**% Difference from Tax**
CAFE	-2,253	-56	-4701%
VES	303	7.6	519%
GHG Tax - Match Trans	49	1.2	0%
Perceived Private Cost	**2011-2050**	**Annual Average**	**% Difference from Tax**
CAFE	2,746	69	1211%
VES	1,604	40	666%
GHG Tax - Match Trans	209	5	0%
Expected Resource Cost	**2011-2050**	**Annual Average**	**% Difference from Tax**
CAFE	1,497	37	784%
VES	1,279	32	655%
GHG Tax - Match Trans	169	4	0%

A breakdown of techno-economic cost flows in the personal transportation sector for the CAFE and VES is shown in

Table 16. Under both of these policies, the personal transportation sector experiences TEC savings from reduced overall capital and fuel costs, but the savings under the CAFE standard are more than double the savings under a VES for all periods. While savings in fuel costs were expected since higher efficiency cars are gaining market share, savings in capital costs was not expected since higher efficiency/lower emitting motors are more expensive. As

Table 16 shows, capital cost savings can be explained by a shift to smaller vehicles in both policy scenarios. Smaller vehicles are less expensive and have better fuel economy. Even though the motors of the cars are more costly under both scenarios, CIMS finds that the savings from shifting to smaller vehicles exceeds the additional costs of the motors.

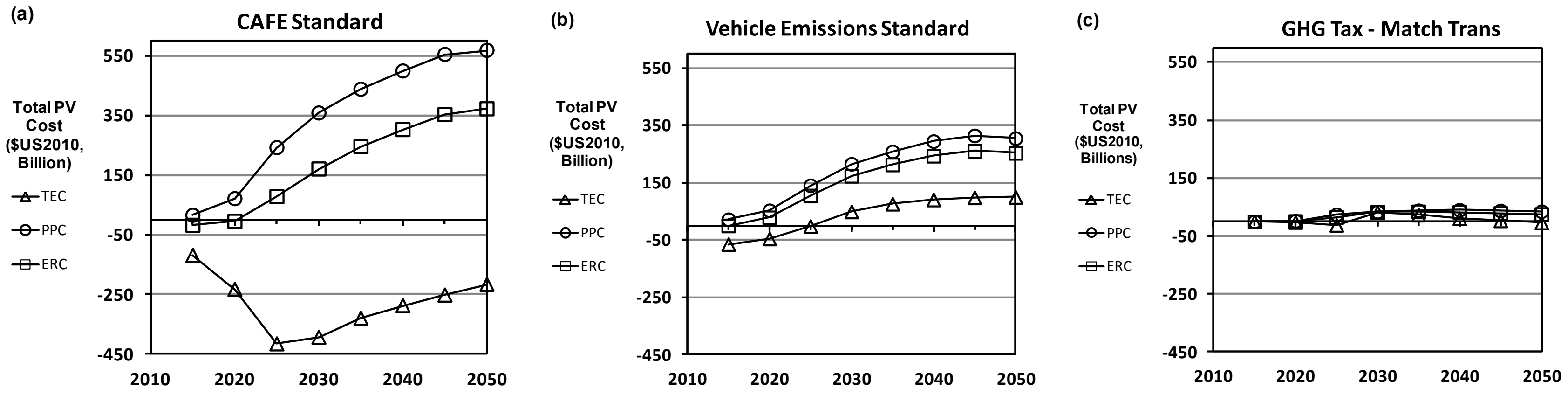
Table 16 TEC Breakdown – CAFE and VES

Techno-Economic Cost Flows in Personal Transportation Sector for 5-Year Period
$US2010 Billions, discounted to 2012 at r = 5%

CAFE	**2020**	**2030**	**2040**	**2050**
Net TEC	-266	-523	-446	-355
Δ Capital Cost	-135	-135	-72	-46
ΔVehicle Shell	-133	-156	-116	-90
ΔMotor	-2	21	44	44
Δ O&M Cost	7	13	11	8
Δ Energy Cost	-138	-402	-385	-317

VES	**2020**	**2030**	**2040**	**2050**
Net TEC	-126	-191	-170	-131
Δ Capital Cost	-69	-50	-30	-15
ΔVehicle Shell	-66	-69	-50	-34
ΔMotor	-3	19	20	19
Δ O&M Cost	4	7	6	4
Δ Energy Cost	-62	-148	-146	-120

Figure 5 Total Cost – Transportation Policies



The PPC is nearly a mirror image of the TEC. Whereas the TEC finds the CAFE standard has the greatest cost savings, the PPC finds the CAFE to be the most costly, at $69 billion a year on average over the forty year simulation period. Figure 5a shows the greatest difference between these two measures occurs in periods 2025 and 2030, with approximately $700 billion separating the two for each period. According to the PPC method, the VES is considerably less costly at $40 billion a year, and the economy-wide GHG tax achieves equivalent emission reductions at a cost of $5 billion a year – just under 10% of the cost of the CAFE.

The difference between the TEC and PPC measures can be seen clearly in Figure 5. A noticeable pattern in Figure 5's graphs is that while the distance between the TEC and PPC measure is quite large under a CAFE scenario, the distance is almost negligible under a GHG tax. As well, a gap exists in the VES scenario, but it is much smaller than the gap in the CAFE scenario. This pattern indicates why energy efficiency policies, like the CAFE, are vulnerable to a greater level of controversy in estimating cost impacts than policies targeting emissions. Depending on one's definition of "cost" the CAFE can appear to generate substantial financial savings or generate substantial welfare losses.

The wide difference between the TEC and PPC estimates can be explained by high intangible costs for technologies in this sector. The dominance of the gasoline engine and gasoline fueling infrastructure means that alternative fuel technologies have substantial intangible costs. Consumers buying vehicles also tend to have higher discount rates than utilities when deciding on capital investments. CIMS sets the discount rate for utilities at 12.5% and vehicle buyers at 25%. Higher discount rates put more weight on the upfront capital costs of an investment, thus penalizing high efficiency cars with higher capital costs.

Since the TEC and PPC measures have such opposing findings for the CAFE, the ranking of the CAFE and VES according to the ERC is quite sensitive to one's assumption on the magnitude of false perceived costs. This study assumes that 25% of the difference between the PPC and the TEC are false perceived costs. By this assumption, the expected resource cost measure finds the CAFE is 15% more costly than the VES at a present value of $37 billion and $32 billion a year on average, respectively, over the forty year simulation period. If the magnitude of false perceived costs is increased to 30%, the cost of the CAFE and VES is virtually identical, and at 35%, the CAFE is 13% less costly than the VES.

By the standard ERC measure, the CAFE and VES are about 8 times as costly as the GHG tax, which highlights the question – why is the US government focusing so much on the transportation sector to deliver GHG emissions reductions? To economists' chagrin, the answer is that cost-effectiveness seems to be taking a back seat to other political priorities and legal requirements. Vehicle efficiency regulations have existed since the 1970s due to concern over sudden oil supply crunches. Oil security is still a major concern of both the Republican and Democratic parties, thus increasing vehicle efficiency to increase oil security is arguably the easiest policy to implement in political terms. The fact that a CAFE standard generates substantial techno-economic cost savings also gives politicians an additional justification for this policy.

5.3. Combined Electricity and Transportation Policies

Currently in the United States, electricity and personal transportation sector policies to reduce GHG emissions are being pursued simultaneously. Due to the interdependent relationship of the electricity and personal transportation sectors, the economic and environmental impacts of policies in these two sectors are different when they are considered together as opposed to if they are each considered separately. To estimate these differences, three policy combinations were run in CIMS-US: (1) a clean electricity standard (CES) and a CAFE standard, (2) a CES and a vehicle emissions standard (VES), and (3) a CES, VES, and an ethanol production emissions intensity standard (EES). The latter policy was added because equating GHG emissions at the economy-wide level of the CES&CAFE and CES&VES was not possible. With a CES, the GHG emissions intensity of electricity is lower than ethanol. Since a VES results in more electricity and ethanol consumption than the CAFE standard, the overall emission reductions under a CES&VES policy are less than under a CES&CAFE policy. To equate emissions at the economy-wide level, I had to add another policy scenario that combines a CES, VES, and an ethanol emissions standard (EES). Lastly, a carbon tax policy is found that results in equivalent GHG emission reductions as the CES&CAFE and the CES&VES&EES.

The stringency of each policy is shown in Table 17. The CES is set to the same level as in the first set of policies, achieving ~60% clean generation by 2040 and ~80% by 2050. Although the percentage of clean electricity is the same, total generation is higher with the combined electricity and transportation policy scenarios on account of the increased electricity demand from the CAFE and VES respectively. The CAFE standard is set to equal the stand-alone CAFE standard in the second set of policies, increasing fuel economy by 3 times 2005/2010 levels by 2050. The VES standard is the same as the VES in the second set of policies, achieving an 89% decrease in emissions intensity of driving from 376 gCO_2/mile to 43 gCO_2/mile. The VES is set to match the emission reductions in the personal transportation sector achieved by the CAFE. The ethanol emissions standard (EES) reduces the GHG intensity of ethanol production from 0.05 to 0.01 tonnes CO_2e/GJ ethanol produced in 2050. Without a policy, ethanol production emissions are 0.04 tonnes CO_2e/GJ ethanol in 2050.

Table 17 Policies – Combined Electricity and Transportation

CES&CAFE		**2010**	**2020**	**2030**	**2040**	**2050**
CES	(% Clean Electricity)	29%	28%	27%	60%	82%
CAFE	(miles/gallon)	24	36	51	62	72
CES&VES		**2010**	**2020**	**2030**	**2040**	**2050**
CES	(% Clean Electricity)	29%	28%	27%	57%	80%
VES	(g CO2 / mile)	376	243	115	75	50
CES&VES&EES		**2010**	**2020**	**2030**	**2040**	**2050**
CES	(% Clean Electricity)	29%	28%	27%	59%	81%
VES	(g CO2 / mile)	376	243	117	75	50
EES	(tonnes CO2 / GJ ethanol produced)	0.05	0.04	0.02	0.01	0.01
GHG Tax - Match Elec & Trans		**2010**	**2020**	**2030**	**2040**	**2050**
Tax	($US2010 / tonne CO2e)	0	17	69	233	233

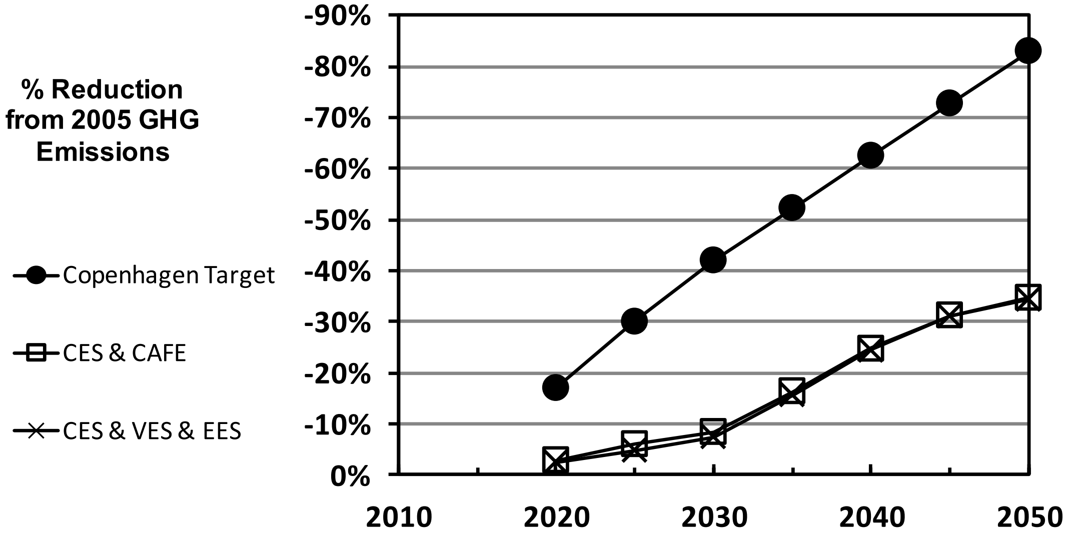
The economy-wide and sector-level GHG emissions of each policy scenario are shown in Table 18, demonstrating that the GHG emissions of the CES&CAFE, CES&VES&EES, and economy-wide GHG tax scenarios are all equal. Note that without the ethanol emissions standard, the GHG emissions of a combined CES & VES policy are 500 Mt CO_2e higher in 2050, which is largely a result of increasing emissions in the ethanol production sector caused by increased demand of ethanol from the VES. The CAFE scenario does not experience increased emissions in the ethanol sector compared to the business as usual scenario.

While these policies achieve substantial emission reductions compared to the BAU scenario, CIMS-US finds they are far from achieving the US's Copenhagen commitments of 42% below 2005 levels in 2030, and 83% below 2005 levels in 2050. As shown in Figure 6, the CES&CAFE and the CES, VES & EES achieve emission reductions of about 8% below 2005 levels by 2030, and 35% below 2005 levels by 2050.

Table 18 Annual GHG Emissions – Combined Electricity and Transportation Policies

Greenhouse Gas Emissions (Gt CO2e)		**2010**	**2020**	**2030**	**2040**	**2050**
BAU	**Economy-wide**	**6.4**	**6.5**	**6.7**	**7.2**	**7.9**
	Electricity	2.2	2.1	2.1	2.3	2.7
	Transportation	1.4	1.5	1.6	1.8	2.0
	Ethanol	0.0	0.0	0.1	0.1	0.1
CES & CAFE	**Economy-wide**	**6.4**	**6.4**	**6.0**	**4.9**	**4.3**
	Transportation	1.4	1.4	1.0	0.8	0.6
	Electricity	2.2	2.0	1.9	1.2	0.6
	Ethanol	0.0	0.0	0.1	0.1	0.1
CES & VES	**Economy-wide**	**6.4**	**6.4**	**6.2**	**5.3**	**4.8**
	Transportation	1.4	1.4	1.0	0.8	0.6
	Electricity	2.2	2.0	1.9	1.2	0.6
	Ethanol	0.0	0.1	0.2	0.4	0.5
CES & VES &EES	**Economy-wide**	**6.4**	**6.4**	**6.1**	**5.0**	**4.3**
	Transportation	1.4	1.4	1.0	0.8	0.6
	Electricity	2.2	2.0	1.9	1.1	0.6
	Ethanol	0.0	0.1	0.1	0.1	0.1
GHG Tax Match Elec & Trans	**Economy-wide**	**6.4**	**6.4**	**6.0**	**4.9**	**4.2**
	Electricity	2.2	2.0	1.7	1.1	0.8
	Transportation	1.4	1.5	1.5	1.5	1.4
	Ethanol	0.0	0.0	0.1	0.1	0.1

Figure 6 Emission Reductions Compared to Copenhagen Target



Once again, the techno-economic cost (TEC) measure and the perceived private cost measure (PPC) are vastly different for these policy scenarios (see Table 19). The TEC measure finds the CES&CAFE policy saves $1.7 trillion over forty years or $44 billion a year on average (present value). Similar to the stand-alone CAFE scenario, these TEC savings are mostly explained by a switch to smaller vehicles under a CAFE standard and fuel savings from higher efficiency vehicles. The techno-economic savings of the CES&CAFE are lower than under the stand-alone CAFE scenario due to the additional techno-economic costs of the CES.

While the TEC measure finds cost savings from a CES&CAFE policy, the perceived private cost measure finds this policy has a PV cost of about $3.6 trillion over the forty year period, 2011-2050, or $90 billion a year on average. Since the difference between TEC and PPC consists of perceived intangible costs, the intangible costs associated with a CES & CAFE policy amount to nearly $5.4 trillion over forty years, or about $134 billion a year on average.

The TEC and PPC measure for the CES, VES, & EES scenario are also quite different. While the TEC for this policy is $17 billion a year on average, the PPC is $63 billion a year on average. Thus the intangible costs associated with this policy are $1.8 trillion over forty years, or $46 billion a year on average.

Table 19 Total Cost – Combined Electricity and Transportation Policies

Total Cost of Policy (US$2010 Billions, discounted to 2012 at r = 5%)

Techno-Economic Cost	2011-2050	Annual Average	% Difference from Tax
CES&CAFE	-1,753	-44	-442%
CES&VES	727	18	42%
CES&VES&EES	693	17	35%
GHG Tax **Match Elec and Trans**	513	13	0%
Perceived Private Cost	**2011-2050**	**Annual Average**	**% Difference from Tax**
Total - CES & CAFE	**3,615**	**90**	546%
CES (with CAFE)	844	21	
CAFE (with CES)	2,771	69	
Total - CES & VES	**2,300**	**58**	311%
CES (with VES)	699	17	
VES (with CES)	1,601	40	
Total - CES & VES & EES	**2,526**	**63**	352%
CES (with VES & EES)	766	19	
VES (with CES & EES)	1,591	40	
EES (with CES & VES)	169	4	
GHG Tax **Match Elec and Trans**	**559**	**14**	0%
Expected Resource Cost	**2011-2050**	**Annual Average**	**% Difference from Tax**
CES & CAFE	2,273	57	315%
CES & VES	1,907	48	248%
CES & VES & EES	2,068	52	278%
GHG Tax **Match Elec and Trans**	548	14	0%

Despite the differences in cost between the TEC and PPC measures, the expected resource cost of the combined electricity and transportation scenarios is fairly comparable at $2.3 and $2.1 trillion over forty years, or ~$50 billion a year on average. Given that the US Gross Domestic Product (GDP) in 2010 was $14.5 trillion, the ERC measure estimates the average annual cost of these policies at 0.4% of annual US GDP.

In comparison, an economy-wide GHG tax would achieve equivalent emission reductions at about $550 billion over forty years according to the ERC measure. Thus the GHG tax achieves emission reductions of 35% below 2005 levels by 2050 at a quarter of the cost of the combined CES and transportation policy scenarios.

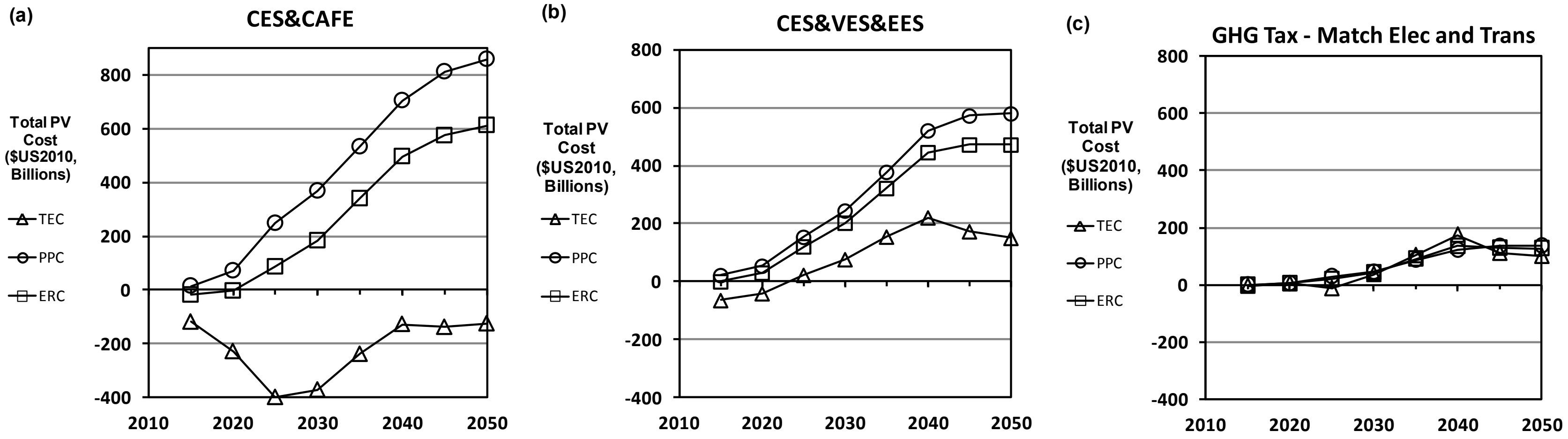
Figure 7 shows the cost dynamics for these policy scenarios over the forty year simulation period. Generally speaking, these diagrams show that costs for all policies and by all measures stay relatively low from 2011-2020, and then starting in 2021, costs increase steadily. For most policies and measures, costs then start to level off after 2040, even though the stringency of the policies increases during these periods. This pattern of a cost "plateau" is caused in part by the declining capital and intangible cost functions within CIMS. These policies encourage the consumption of higher efficiency/lower emission technologies, increasing learning by doing, infrastructure and performance information associated with these new technologies, and thus decreasing their capital and intangible costs. This pattern demonstrates how investments made in meeting a standard in the short-term reduce costs for meeting more stringent standards in the long term. Such a pattern has also been empirically observed in the implementation of the US regulations on sulphur dioxide emissions (Taylor et al., 2005), and Grubb (1997) provides a good theoretical discussion on the relationship between abatement costs and the timing of climate change policies.

Another reason for the "plateau" is discounting. Undiscounted costs are increasing in every period, however, while the undiscounted costs in 2021-2040 are increasing at a higher rate than the discount rate, the undiscounted costs from 2041-2050 are increasing at an equal or lower rate than the discount rate.

Since electricity generation increases with both the CAFE and VES, the cost of the clean electricity standard also increases when these transportation policies are implemented. The PPC of the stand-alone CES is $670 billion over forty years. When a CAFE is added to the CES, the PPC for the CES increases to $844 billion over the same period. When a VES is added to the CES, the PPC for the CES increases only slightly to $699 billion since fuel switching under this policy is primarily shifting from gasoline to ethanol. But when an ethanol emissions standard is added to a VES and CES, ethanol becomes more expensive and fuel switching is split between ethanol and electricity, increasing the cost of the CES to $766 billion.

Interestingly, although a slight increase in the price of electricity occurs when a CES is combined with a CAFE and VES&EES, this increase does not change the PPC of the CAFE and VES compared to when the policies were simulated on their own. The difference between the PPC of the stand-alone CAFE and the CES&CAFE is ~$25 billion over forty years, a tiny fraction of the total cost of $2.7 trillion. The PPC for the stand-alone VES and the CES&VES differs by only a few billion over forty years. This indicates that a slight increase in electricity price has a negligible effect on the choice of vehicle under a CAFE and VES.

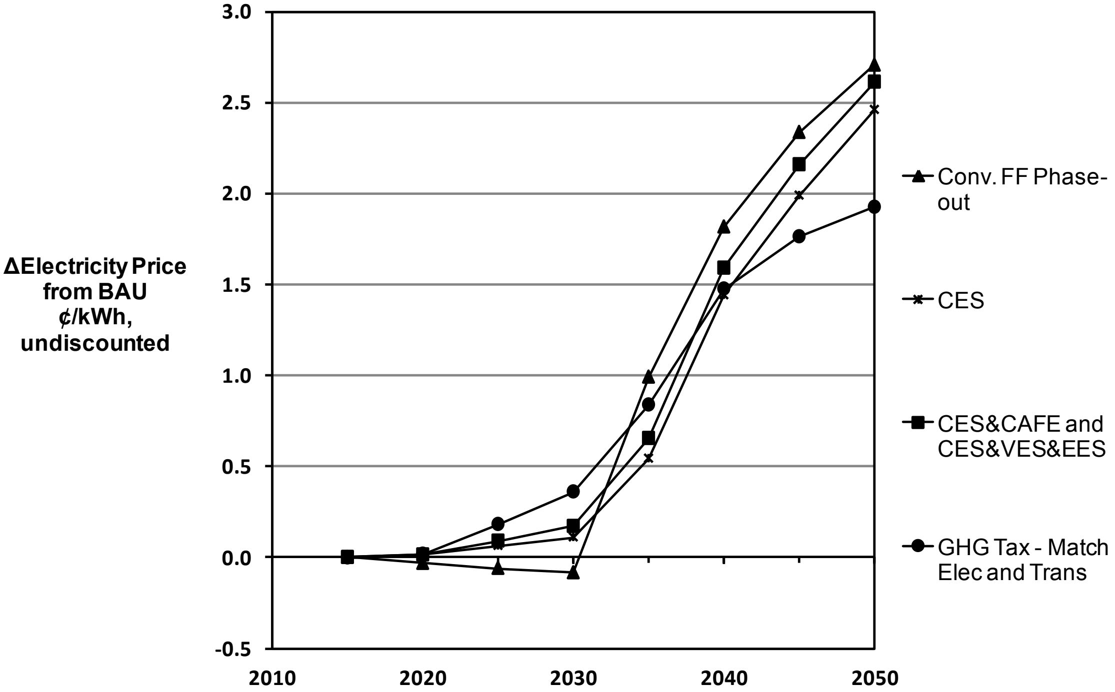
Figure 7 Total Cost - Combined Electricity and Transportation Policies



5.4. Electricity Price Changes

All of the scenarios with electricity policies result in electricity price increases relative to the business as usual scenario. Figure 8 depicts these increases for select policies in undiscounted ¢/kWh. Recall that the cost of shadow emission charges and taxes is recycled back to the sector, so this cost is not included in the price of electricity. Electricity price increases are purely a factor of increased production costs in response to the policy.

Figure 8 Change in Electricity Price



CIMS-US finds the policy to phase-out conventional fossil fuel generation leads to electricity price *decreases* from 2016-2030 of about 0.03-0.08 ¢/kWh. Prohibiting generation from coal encourages the uptake of more natural gas in the period 2016-2030. Since coal generation has a higher levelized cost than natural gas, replacing coal with natural gas generation actually saves costs in the electricity sector for this initial period. From 2031-2050, the Conv. FF phase-out policy results in higher electricity price increases compared to a clean electricity standard because it prohibits new natural gas generation after 2031, which has the lowest levelized cost out of all the generation options. Thus forcing a switch from natural gas to any other type of generation technology increases costs relative to a policy that allows natural gas generation to continue.

Figure 8 also shows that the GHG tax policy results in higher electricity price increases than the combined CES & transportation policies from 2021-2035. The GHG tax policy results in higher electricity prices because this policy results in higher levels of clean generation than the CES and transportation policies. Thus one of the reasons that the GHG Tax is less costly overall is because it benefits from achieving greater emission reductions in the electricity sector where abatement costs are lower. This comparison also highlights the danger of judging the total cost of a policy purely by its increase in electricity price.

Change in household expenditure on electricity in 2050 relative to BAU is shown in Table 20. Except for the GHG tax scenario, the financial cost of an increase in the electricity price is partially offset by reduced electricity consumption within the house (not including vehicles). For scenarios with transportation policies and the GHG tax, the electricity price increase is fully offset by a reduction in vehicle fuel costs as gasoline motors are replaced by electric motors.

Table 20 Change in Household Expenses in 2050 from BAU, undiscounted

	Δ Electricity Price ¢US2010/kWh	**ΔElectricity Consumption (not including vehicle)** kWh/month	**Δ Household Electricity Expenditure (not including vehicle)** $US2010/month	**Δ Household Vehicle Fuel Costs** $US2010/month
Conv. FF Phase-Out	2.71	-91	31	0
CES	2.46	-77	29	0
CES&CAFE	2.61	-86	30	-221
CES&VES&EES	2.49	-82	29	-98
GHG Tax - Match Elec & Trans	1.92	101	26	-61

In 2050, the highest increase in electricity price above BAU under these policies is 2.71 ¢/kWh under the phase-out of conventional fossil fuel generation. Electricity consumption per household is 1,147 kWh/month under this policy, lower than the 1,237 kWh/month of the BAU scenario. Given the lower electricity consumption, this policy would result in an increase of $31 per month for the average household over what they would pay with no policies (in $2010US, undiscounted). The lowest increase in 2050 is 1.92 ¢/kWh for the GHG tax that matches the emission reductions of the combined electricity and transportation policies. Electricity consumption per household under this GHG tax is 101 kWh more than BAU in 2050 because households shift from natural gas to electricity under a GHG tax, but the overall increase in electricity expenditure is still less at $26/month. The increased expenditure on electricity under a GHG tax is the net effect after a GHG tax has been collected and then revenue is returned to utilities based on the amount of electricity they produce.

5.5. Putting Costs into Context

The preceding sections showed that economy-wide GHG tax policies are the least costly way to reduce GHG emissions compared to sector-level and technology-specific policies. An average person or policy-maker reading this analysis may be more interested in the *absolute costs* of these policies rather than their *relative costs* to each other. Consideration of the absolute costs of policies could lead to the following types of questions:

1. Can the US afford to implement any of these policies at this time?
2. Do the benefits of reduced exposure to climate change and reduced fossil fuel consumption make up for the costs of implementing the policies?

In a recent op-ed in the *New York Times,* economist Paul Krugman remarked that media coverage over the cost of GHG emissions abatement was suffering from the same biased reporting as climate change science, stating “the casual reader might have the impression that there are real doubts about whether emissions can be reduced without inflicting severe damage on the economy” (Krugman, 2010). The opinion of Americans on the economic impacts of climate change policies is hard to gauge as there is a surprising lack of survey data on this question. The majority of public opinion surveys in the US have focused on whether or not Americans believe anthropogenic climate change is occurring and if it is a problem worth addressing. Nevertheless, as Paul Krugman states, spokespeople are often heard in the media criticizing potential GHG regulations in terms of their impact on the economy, thus some American citizens are surely wondering if the U.S. can afford to reduce GHG emissions.

A typical economist response to questions around economic impact is often to estimate the net percentage change in gross domestic product from the costs and benefits of a climate change policy, but this measure holds little meaning for the average person. Randy Olson, paraphrasing Martin Palmer, states “data per se has no persuasive power at all. The only persuasive power it has is if it goes into a context where it is interpreted” (Olson, 2012).

To give context to the affordability and benefits of these climate change policies, I compare the policy costs calculated in this study to the cost of achieving other societal and private values. Admittedly, this approach is much more of an “art” than a “science”, thus it should not be thought of as a rigorous analysis. Rather, the intention is to provide some tangible reference points to stimulate self-reflection and dialogue on the meaning of a policy cost. The only modification that I did to standardize costs/values across examples was to bring each cost estimate into an annual cost estimate by dividing its total cost by the number of years the example spans. As well, all costs were converted into $2010US and rounded to the nearest billion dollars.

To review the findings from this study, the combined electricity and transportation policies achieve GHG emission levels of 4.3 Gt CO_2e/year, or a reduction of 35% below 2005 levels by 2050. While these policies on their own would not achieve the US Copenhagen target of 1.1 Gt CO_2e /year by 2050, they get the US half way to its target considering the BAU trajectory is 7.9 Gt CO_2e/year. The CES increases the proportion of zero-GHG emission electricity generation from 30% in 2015 to 80% in 2050. The CAFE improves fuel economy by three times from 2010 to 2050, from 24 miles per gallon (mpg) to 72 mpg. The VES decreases the GHG emissions intensity of driving by 89%, from 376 gCO_2e/mile to 50g CO_2e/mile. The GHG tax matches the emission reductions of the combined electricity and personal transportation sectors by applying an economy-wide tax of $20/tonne CO_2e in 2020, increasing to $233/tonne CO_2e in 2050.

As discussed in Section 4, I made conservative assumptions about future conditions in the version of CIMS-US used in this study. By “conservative” I mean assumptions in the model were set to make emissions abatement more costly, representing a “pessimistic” view of the progress of higher efficiency and lower emission technologies. For example, I limited the amount of nuclear generation, the lowest cost alternative to fossil fuel generation, forcing the uptake of more expensive renewable and CCS generation. As well, I placed high intangible costs on alternative fueled vehicles and a 2$^{¢}$/kWh storage cost was added to intermittent renewable generation. By evaluating an upper bound on costs, the costs of implementing these policies in reality would likely be lower than found in this study, as technological innovation or behavioural change would occur that is not captured within CIMS-US. However, the possibility exists that policy costs could be higher than estimated. Numerous assumptions are made within CIMS about future energy prices and resource availability, thus these policy cost estimates are dependent on those assumptions. As well, there could still be “unknown, unknowns” in the cost of implementing these policies that are not included in CIMS.

The first question of the “affordability” of the policies is concerned with dollars and cents, i.e., does the cash flow exist to incur extra costs for cleaner electricity generation, transportation, and overall GHG reduction, or will the U.S. “go bankrupt” implementing these policies? For the question of affordability, I’ll focus on the expected resource cost of the clean electricity standard and the GHG tax to match the emission reductions of the combined electricity and transportation policies, which have a present value cost of $17 billion and $14 billion on average per year, respectively, consisting mostly of increased capital costs. I leave out consideration of the transportation policies in discussing affordability since these policies generate large techno-economic savings.

Perhaps examining what the U.S. spends on non-essential consumption items will help to put the affordability of the CES and GHG tax into context. The most obvious example of non-essential consumption I can think of is expenditure on cosmetic surgery, which in 2009 was $10 billion (Siew, 2009), just under the cost of the GHG tax. One could also easily argue expenditure on gambling activities is an example of non-essential spending. The gambling revenue from US commercial casinos in 2011 was $36 billion a year (Spain, 2012), over double the cost of the CES and GHG tax.

As well, one could think about expenditure on goods that claim they will help people, but often are just the equivalent of “snake oil”. Many goods in the area of weight loss and diet control could be considered as part of the “snake oil” category. U.S. expenditure on weight loss and diet control goods and services in 2010 was valued at $61 billion (Marketdata Enterprises, 2011), quadruple the cost of the CES and GHG tax.

Expenditure on non-essential goods can also be considered at the individual level. For example, the amount spent by the average American worker on going out for lunch was $1,270 in 2011, for a total of $181 billion (Accounting Principals, 2012), most of which is spent on unhealthy fast food (Workman, 2007). Under a CES, the additional cost of electricity for the average household is estimated to be $60/year in 2035, in undiscounted 2010 US dollars, less than 5% on what an average worker spends on going out for lunch.

Another way to look at compensation for these additional monetary costs is to consider that these policies reduce the production and consumption of fossil fuels, and thus will reduce the level of damages caused by the fossil fuel industry. "Damages" includes the monetary costs of damaged property or increased expenses, as well as the non-monetary cost of reduced quality of health and the environment. Consideration of damages addresses the second question of whether the benefits of implementing the policies make up for their costs.

CIMS estimates that the combined electricity and transportation policies and the GHG tax would reduce consumption of coal at least 65% from BAU levels in 2050. A study by the Harvard Medical School estimates the damages of the waste streams from coal, including, the monetizable impacts due to climate change (thus does not include the extinction of species); public health damages from NO_x, SO_x, $PM_{2.5}$, and mercury emissions; fatalities of members of the public due to rail accidents during coal transport; the public health burden in Appalachia associated with coal mining; government subsidies and lost value of abandoned mine lands. This study finds the cost of coal to the U.S. public is between \$300-\$500 billion annually (Epstein et al, 2011). This cost is 5-9 times higher than the ERC of the CES&CAFE policy and 22-37 times higher than the GHG tax.

Another good comparison is the cost of potential damages associated with accidents from petroleum extraction and transportation. The CAFE and VES policies in this study reduce consumption of total refined petroleum in the US by 50% in 2050 compared to 2005 consumption levels, or 70% from BAU levels in 2050. If this reduced level of petroleum consumption corresponds to reduced levels of petroleum extraction in the US, then the US is at lower risk of sustaining damage from oil spills. Etkin (1999) estimates that the average cleanup cost for oil spills on land is \$118 per gallon oil spilled. Between 1987 and 1999, approximately 125 million gallons of oil were spilled on U.S. soil (Etkin, 2001), amounting to an average financial cost of over \$1 billion a year for that period.

But cleanup costs are only a portion of the full social cost of these spills. One indication of the social cost of a spill is the compensation payments oil companies have to pay to victims. The BP oil spill in the Gulf of Mexico in 2010 is one recent example.

The liability of BP in clean up and compensation costs is estimated to be $40 billion (BBC, 2010). In addition, many citizens, businesses, and ecosystems have sustained damage that will never be compensated.

Recall that the expected resource cost of the CAFE is estimated by CIMS as $37 billion a year and the VES is $32 billion a year. A reduction in damages from the extraction and transportation of oil could make up for part, but likely not all, of the loss in value from implementing the CAFE and VES. But reducing oil consumption also has other values, such as helping to achieve the US goal of energy independence.

One indicator for how much the US values energy independence is the amount of money the U.S. government spends on subsidies to both the fossil fuel and biofuel industries in pursuit of this goal. For example, conservative estimates of direct subsidies and tax breaks for fossil fuels are $10 billion a year (OECD, 2012). When subsidies to help secure importation routes for fossil fuels are considered, this estimate goes up to $40-69 billion a year (Koplow, 2004; Koplow, 2007). Subsidies for biofuels are also substantial –$24 billion in 2012 and they are set to increase in the coming years (Steenblik, 2007). This indicates that the U.S. values the goal of energy independence at about $34-93 billion, which is more than the loss of value in implementing the CAFE and VES. Moreover, since either the CAFE or VES would make more progress towards the goal of energy independence than current subsidies to fossil fuels and biofuels, these subsidies could be eliminated and taxes lowered.

Of course, all of these policies will reduce GHG emissions and mitigate damages from climate change. Implementing these policies on their own however, will not be sufficient for avoiding dangerous levels of climate change. The combined electricity and transportation policies are estimated to bring GHG emissions from energy consumption 35% below 2005 levels by 2050. To avoid dangerous levels of climate change, the US needs to achieve an 80% reduction in emissions, along with all other developed countries, and developing countries also need to decrease their emissions. Since more policies will be needed to achieve this goal, the costs of the policies modeled in this study can not be compared directly to estimated damages in a traditional cost-benefit sense. However, I will provide a few estimates of damages to give a sense of potential losses if no policies are implemented.

One risk of increasing global average temperatures is the increased occurrence and severity of some natural disasters, such as hurricanes, to which the US is particularly vulnerable. Indeed, there has been an increase in the frequency of storms over the 1851-2005 period, particularly since 1980, and the increase in hurricane frequency is positively and significantly related to sea-surface temperatures in the North Atlantic (Nordhaus, 2010). As well, Emanuel (2005) has found an increasing trend in the intensity of storms in the North Atlantic over the last three decades. Increasing severity of storms could explain why Hurricane Katrina in 2005 was (in inflation-corrected prices) the costliest hurricane in US history. The estimated damages to private and public infrastructure of hurricane Katrina is estimated to be $162 billion (Burton and Hicks, 2005).

To estimate future damages caused by hurricanes as a result of greater global temperatures, Nordhaus (2010) uses a damage intensity function for hurricanes for a scenario where atmospheric CO_2e concentrations double by 2100. Nordhaus finds that average annual hurricane damages will increase by $10 billion, or 0.08% of GDP at the 2005 level, due to the hurricane intensification effect of a CO_2-equivalent doubling.

Another consequence of rising carbon emissions is the loss of coral reefs, which are harmed by both rising sea temperatures and increased ocean acidity. A recent study commissioned by the National Oceanic and Atmospheric Administration estimates that the U.S. public values Hawaii's coral reef ecosystem at $34 billion a year. In this study, total economic value includes the willingness to pay to protect the coral reef ecosystem for future generations, as well as direct use values, such as snorkeling over a coral reef or consuming fish supported by coral reef ecosystems (NOAA, 2011).

Increased severity of hurricanes and the loss of coral reefs are just some of the phenomena that would impose damages with rising global average temperatures. Additional areas of damage for the United States include rising sea levels, changes in agricultural productivity, human health impacts, property damages from increased flood risk, and changes in the value of ecosystem services. As well, especially at lower levels of temperature increase, the potential exists for temperature increases to result in some benefits to the US, for example from reduced need for space heating and increased levels of agricultural productivity. The main method of estimating the net level of damage or benefit caused by a temperature increase is through using a computable general equilibrium (CGE) model.

Jorgenson (2004) applies a CGE model to assess the potential levels of damage to the United States. While this paper is not trying to provide a full cost-benefit analysis, it may nevertheless be useful to keep in mind Jorgenson's conclusion when interpreting policy costs:

> In sum, the disparity in results between optimistic and pessimistic scenarios – and the likelihood that a consideration of non-market impacts would tend to exacerbate this disparity – highlights the continuing uncertainty associated with quantifying climate change impacts. The fact that the economic losses associated with pessimistic scenarios are both larger and more continuous than the transient benefits gained under optimistic scenarios would seem, by itself, to provide some support for cautionary action on climate change.

Jorgenson's conclusion along with the earlier discussion around the affordability and benefits of cleaner generation and transportation are a starting point for putting these policy costs into context, and sparking discussion, reflection and further analysis. While I am not suggesting that this approach to putting costs into context take the place of more complete, objective and rigorous analyses, I am suggesting that this method is more conducive to forwarding understanding of an issue at a scale larger than a small research community.

6. Conclusion

6.1. Major Findings

This study analyzes the cost-effectiveness of different climate change policy instruments according to three different measures of “cost”. While the different methodologies of measuring cost did not impact the ranking of policies for the electricity in terms of their cost-effectiveness, it did impact the ranking of policies in the transportation sector.

When using the “top-down” methodology for costing, or the perceived private cost measure, I find that the cost-effectiveness of policies follows the general theory that the greater the opportunities for abatement, the lower the costs. In other words, for a given GHG emissions reduction target, costs are lower for policies that cover more emissions and allow for more flexibility in complying with the policy. For the electricity sector policies, the clean electricity standard is less costly than the coal and natural gas generation phase-out because the CES provides for greater flexibility in how emission reductions are achieved. By focusing the policy on the end goal – lower GHG emissions intensity of generation – the CES can achieve the same emission reductions without the costly requirement of demanding zero market share of coal and natural gas plants.

Likewise, the comparison of transportation policies finds that the corporate average fuel economy (CAFE) standard is just about double the perceived private cost of the vehicle emissions standard (VES). The VES achieves cost savings relative to the CAFE standard because the VES can reduce emissions by switching from gasoline to ethanol and by improving vehicle energy efficiency. The CAFE standard can only reduce emissions through improving vehicle energy efficiency. The high perceived cost of the CAFE standard represents the fact that a portion of consumers currently value large vehicles and the longer range of gasoline and ethanol motors. Thus consumers experience less perceived cost if a policy allows for emission reductions through fuel switching as well as energy efficiency.

However, a portion of the perceived costs of the CAFE standard could also result from false perceived costs due to market failures. When using a “bottom-up” methodology for costing, or the techno-economic cost, the CAFE standard is found to be the least costly, generating savings of about one trillion dollars over 40 years. While the perceived private cost measure finds the CAFE standard to be the most costly policy, producing one trillion dollars in losses. This distance between the TEC and the PPC means that intangible costs represent 2 trillion dollars of cost, thus the magnitude of false perceived costs is likely quite large.

The rule-of-thumb of my research group is that 25% of the difference in cost between the TEC and the PPC are false perceived costs due to market failures. A better approximation of the true welfare losses of a policy then are to subtract this 25% from the PPC to get a measure that we call the expected resource cost. Going by this general rule, the expected resource cost of the CAFE is slightly more costly than the VES.

Since the expected resource cost measure is currently based on the judgement of experienced CIMS modelers, research could be done to improve and/or document the empirical basis for this technique. Because of the uncertainty in the true proportion of the PPC that represents false perceived costs, this study can not conclusively state whether a CAFE or VES policy is more cost-effective. However, these results do give reason to challenge the general view that a policy will automatically be lower in costs if it has greater abatement opportunities. While policies with more abatement opportunities tend to be lower in cost, this is not necessarily the case for all policy comparisons. Consider that the equi-marginal principle states that minimizing the cost of reducing a given amount of pollution requires equating marginal abatement costs across all options and agents for reducing pollution (Baumol and Oates, 1988). While emphasis is often put on the latter half of this statement, “across all options and agents”, not much emphasis is put on what it means to “equate marginal abatement costs”. Should a policy aim to equate perceived marginal abatement costs or should the goal be to equate marginal abatement welfare costs?

I would argue a policy should aim to do the latter, as those are the actual costs of a policy. The significance of such an argument is that an economy-wide GHG pricing policy might not be the most optimal policy, in terms of minimizing welfare loss or maximizing welfare gain. An even more optimal policy would be an economy-wide GHG pricing policy combined with energy efficiency performance standards to correct for market failures. A side-benefit of such a combination approach is that reducing market failures with regards to energy efficiency would lower the necessary GHG tax or permit price for achieving a given amount of emission reductions.

As an aside, a similar argument has been made for combining GHG pricing with investments in research & development (R&D). The free market fails to provide optimal amounts of R&D due to the “positive spillover” effect whereby the value of R&D to society is greater than the private value of R&D to firms. Governments can make up for the less than optimal R&D investments of the private sector by investing public funds in R&D. Like correcting market failures in regards to energy efficiency, correcting the R&D market failure in regards to GHG emissions abatement would also reduce the necessary GHG tax or permit price for a given amount of emission reductions.

Returning to the previous discussion, in estimating the total cost of a policy, the typical top-down model uses perceived marginal abatement costs. This modeling methodology is unlikely to conclude, or even consider, that a CAFE policy may result in less welfare costs than a VES, or that a CAFE should be combined with a GHG pricing policy to maximize welfare. Therein lays the value of a hybrid model which can consider the cost of policy from three perspectives – the bottom-up techno-economic cost, the perceived private cost, and the expected resource or welfare cost. Each perspective provides a challenge to the other perspectives, forcing better reflection on the results of the model.

While this study suggests potential benefits of pursuing energy efficiency policies alongside GHG pricing policies, the study finds some drawbacks of pursuing energy efficiency policies on their own. Although the CAFE standard achieved substantial emission reductions in the transportation sector, about a third of those emission reductions were negated by greater emissions in the electricity sector. Or from a different perspective, by 2050, CIMS estimates that a CAFE standard will lower emissions from 21% above 2005 emissions in the BAU scenario to 13% above 2005 emissions. Whereas a CAFE combined with a clean electricity standard will lower 2050 GHG emissions to 34% below 2005 levels.

Similarly, a switch from gasoline to ethanol under a vehicle emissions standard increases the emissions of the ethanol production sector so much that a policy scenario combining a VES and CES policy can not equal the emission reductions of a CAFE and CES policy combination. These two examples represent a general tenet for pursuing sectoral regulations – when regulating an energy demand sector, consider the implications to the energy supply sector.

This tenet also holds for the reverse. The implications of regulating an energy supply sector need to be considered for energy demand sectors. Comparing the two electricity policies demonstrates this finding. The more costly technology regulation increases electricity prices more than the clean electricity standard, resulting in greater switching from electricity to natural gas compared to the CES. Thus the technology regulation results in greater emissions in the energy demand sectors than the CES. The technology regulation also produces higher emissions in the primary energy supply sectors because more coal and natural gas are extracted to supply plants with carbon capture and storage (CCS). While the CES penalizes CCS for the 10% of its emissions that are not captured, the technology regulations do not, resulting in greater CCS under the technology regulation than the CES.

In summary, this study finds substantial potential savings for implementing tradable performance standards over technology regulations. As well, this study estimates that an economy-wide GHG pricing policy is a quarter of the cost of relying on tradable performance standards in the electricity and transportation sector. We know GHG pricing is central to achieving deep emission reductions at a low cost, thus it seems this should eventually happen. But potentially the United States needs some “stepping stones” before making the big leap of economy-wide GHG pricing. Tradable performance standards show promise in providing this bridge. With the right design, tradable performance standards could eventually be traded between sectors, constructing a GHG pricing system from the “bottom-up”.

6.2. Recommendations for Future Studies

This study shows that the flexible hybrid structure of CIMS enables comparative analysis of policies at all levels (technology, sector, economy-wide) and from different perspectives of policy cost. Since the U.S. is currently focusing on technology and sector-level regulations, this modeling structure may become even more valuable. To improve policy costing analysis with CIMS, I would suggest two studies – the first one to focus on providing a more empirical basis for the expected resource cost method, and the second one to compare abatement costs of CIMS with top-down models.

This first study on the ERC method would focus on finding an empirical basis for the percentage of cost between the TEC and PPC that is likely due to false costs from market failures. This study used a rule-of-thumb of 25%. The real percentage could vary between sectors and perhaps even vary depending on the technology. I used the 25% number in this study because I thought it would be sufficient for a cost-effectiveness study, but the similar ERC values of the CAFE and VES meant this choice of 25% has a large influence on which of these policies is determined to be less costly. Along with improving analysis of cost-effectiveness, a stronger empirical basis for the ERC would give more confidence to estimates of the absolute welfare loss/gain of a policy.

Despite the desirability of having a greater empirical basis for the ERC, future research in this area could run into challenges in developing a method to determine the percentage of false perceived costs. While Moxnes (2004) demonstrates the presence of false perceived costs, a method for translating the findings from a study like Moxnes (2004) into an estimate for ERC is not self-evident. Consequently, a student who is familiar with discrete choice methods using stated and revealed preference data would likely have more success at developing such a method. Another starting point could be to search for research on the factors that contribute to high revealed discount rates and the contribution of market failures to these discount rates. However, this research may not exist. Jaffe and Stavins (1994) developed a theoretical model on the adoption of energy efficiency investments whereby they concluded that it is impossible to disentangle the factors contributing to high discount rates from observed purchase decisions, but potentially other methods exist. Given these potential challenges, I think it would be useful for someone to first consider the value of the ERC measure compared to other economic measures that CIMS can produce on its own or when it is soft-linked to a top-down model.

A comparative study of CIMS with top-down models could also improve confidence in estimates of the absolute welfare loss/gain of a policy. CIMS participation in Energy Modeling Forum 24 demonstrated that CIMS requires some of the highest charges on GHG emissions out of all the participant models, which were mostly top-down models. This finding is contrary to the view that a hybrid model such as CIMS should have abatement cots in between conventional bottom-up and top-down models. Thus other factors besides technological explicitness, behavioural realism and macro-economic feedbacks could be influencing CIMS' estimation of abatement costs. A comparative study could attempt to find if CIMS is overestimating abatement costs or CGE models are underestimating abatement costs.

One way to compare abatement costs of CIMS to CGE models is to compare the implicit values of elasticity of substitution in CIMS as found in Bataille (2005) and Baylin-Stern (2012) to values used in CGE models. For example, if the capital-fuel elasticities are found to be lower in CIMS compared to CGE models, energy efficiency investments will be more costly in CIMS. As well, if the inter-fuel elasticities are lower in CIMS than most CGE models, this may indicate that CIMS does not represent as many options as CGE models for switching from fossil fuels to zero-emission fuels, which could either mean that CGE models are overestimating abatement options or CIMS is underestimating abatement options. Another reason abatement costs could be higher in CIMS compared to CGE models is that the sectoral structure of CIMS could be more rigid than a CGE model, inhibiting structural change in response to a policy.

While potential exists to improve confidence in CIMS' estimation of welfare loss/gain, CIMS is limited in its ability to estimate GDP and employment effects because of its partial-equilibrium structure. Especially in the U.S., political debate around most policies, including climate change policy, centers around the impact on jobs. Developing a method to estimate employment effects with CIMS-US results could enable participation in this dialogue. One method that was used with CIMS-Canada was to soft-link CIMS with a CGE model. CIMS simulates the policy and then CIMS results are fed into the top-down model to produce macro-economic impacts such as GDP and job loss/gain.

Future research that uses shadow emissions charges to phase-out technologies should consider that when phasing out technologies in CIMS using this method, large increases in the emissions charge are required to reduce the new market share of a technology from 2% to 0%. The steep slope of this marginal emissions charge is a result of the heterogeneity parameter in the CIMS market share algorithm, which gives a technology new market share even though its life cycle costs are higher than the alternatives. A technology needs to be considerably higher than the alternatives for it to receive no new market share.

Using shadow emissions charges to phase-out technologies in CIMS is beneficial because it allows for the calculation of the perceived private cost and the expected resource cost, but future research should consider if these large increases in emissions charges are justified. On one side, the heterogeneity parameter legitimately represents the fact that completely prohibiting a technology from use can be more costly because particular situations exist where that technology might be clearly superior to the alternatives. On the other side, substantially increasing the shadow emissions charge to reduce the new market share of a technology from 1% to 0% may over estimate the cost of a technology regulation, especially for an energy service where technologies are fairly interchangeable. Each technology regulation may have to be evaluated according to its particular situation, however, some standard “rules of thumb” may be useful when applying this method. An example of a rule of thumb could be that once a technology reaches 1% new market share, if this technology requires an increase in the shadow emission charge of more than $100/tonne CO_2e to further reduce its new market share to 0%, then no further increases in emissions charge are necessary and the technology should just be completely phased out in the next period using the market share limit parameters. This rule of thumb might not be the right one for each situation, it’s just an example of the type of rules future research may want to apply when modeling technology phase-outs in CIMS.

In addition to further research on policy costing methods with CIMS, further studies could be done on applying technology- and sector-specific regulations to other sectors. Due to the increasing marginal cost of emissions abatement, achieving the 2050 Copenhagen target with all technology and/or sector-specific regulations could show a much larger price difference between these types of regulations and an economy-wide pricing mechanism than was found in this study. As well, tradable performance standards may be more difficult to implement or limited in their application for some sectors, such as the residential and commercial sectors. Thus some interesting work could be done to design the most cost-effective technology- or sector-specific regulations in these sectors.

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Appendices

Appendix 1

Discount Rates in CIMS-US

Sector	Technology	Discount Rate
Residential	Space heat/shell	25%
	Appliances	25%
Commercial	Building HVACs	40%
	Appliances & Hot Water	40%
Transportation	Private Vehicle	25%
	Urban Public Transit	25%
Industrial	Process	35%
	Auxiliary	50%
Electricity	Generation	12.5%

Appendix 2

Example Calculation of PPC

The Clean Electricity Standard in this study's US2 scenario required a shadow emission price path as shown in chart directly below. Using this price path, the subsequent steps were followed to calculate PPC.

	2020	2025	2030	2035	2040	2045	2050
CES Price Path ($/tonne CO2e)	17	33	37	166	332	382	498

Step 1: Run shadow emission charges on GHG emissions in Electricity Sector as shown in chart below

GHG Shadow Emission Charge ($/tonne CO2e)

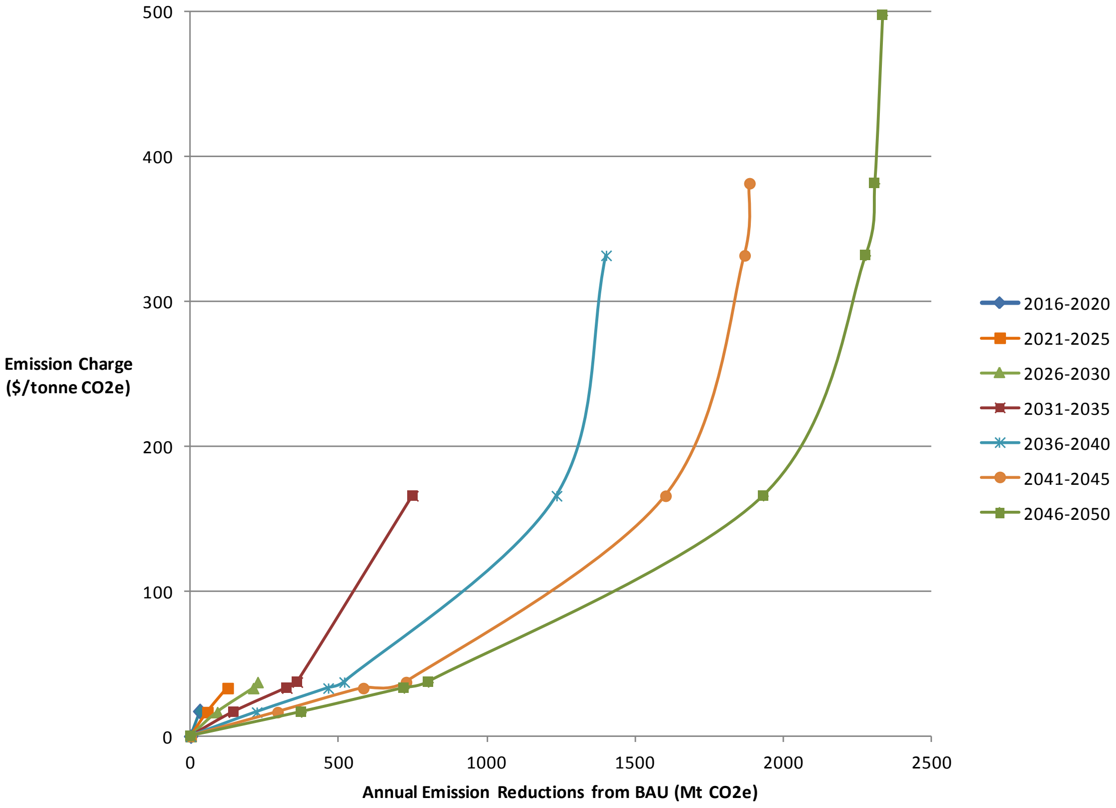
Simulation #	2020	2025	2030	2035	2040	2045	2050
BAU	0	0	0	0	0	0	0
1	17	17	17	17	17	17	17
2	17	33	33	33	33	33	33
3	17	33	37	37	37	37	37
4	17	33	37	166	166	166	166
5	17	33	37	166	332	332	332
6	17	33	37	166	332	382	382
7	17	33	37	166	332	382	498

Step 2: Obtain Annual Economy-wide GHG Emission Reductions from Simulations in Step #1

Economy-wide GHG Emission Reductions (Mt CO2e)

Simulation #	Emission Charge	2020	2025	2030	2035	2040	2045	2050
BAU	0	0	0	0	0	0	0	0
1	17	32	57	90	145	223	293	373
2	33	32	125	211	324	464	582	719
3	37	32	125	226	360	518	727	801
4	166	32	125	226	750	1234	1602	1931
5	332	32	125	226	750	1401	1869	2276
6	382	32	125	226	750	1401	1885	2307
7	498	32	125	226	750	1401	1885	2334

Abatement Cost Curves for Clean Electricity Standard



Step 3: Calculate PPC in each period for each marginal emission charge increase following this equation:

PPC = (Area under the curve of time period) x 3.79
3.79 adds the annual costs and discounts them to first year of the period at a 10% discount rate.

Simulation #	Emission Charge	2020	2025	2030	2035	2040	2045	2050
1	20	1,001	1,784	2,823	4,551	7,014	9,223	11,737
2	40		6,434	11,463	16,972	22,742	27,299	32,701
3	45			1,965	4,728	7,257	19,282	10,936
4	200				150,257	276,051	337,360	435,508
5	400					157,609	251,853	325,764
6	460						22,062	41,943
7	600							44,150

Step 4: Add Columns

	2020	2025	2030	2035	2040	2045	2050
Total PPC for Period, Millions $, discounted to first year in period	1,001	8,219	16,251	176,508	470,673	667,079	902,739
Total PPC for Period, Millions $, discounted to 2012	684	3,485	4,279	28,860	47,785	42,052	35,335