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Carbon Capture and Storage – The Environmental and Economic Case and Challenges

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Carbon Capture and Storage – The Environmental and Economic Case and Challenges

Carbon capture and storage (CCS) is increasingly regarded as critical technology in the effort to mitigate greenhouse gas (GHG) emissions. Both the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) have made it clear that any transition to a carbon-constrained future will require a strong CCS component to succeed. While much attention is paid to the need to implement such technologies in rapidly growing developing economies, such as China and India, CCS is also regarded as a critical technology for developed countries, like Canada, where energy, mining and energy intensive industry sectors are economically important. Canada must view CCS development as a national responsibility that could start in Western Canada, where geology is more favourable, and eventually be applied across the country and around the globe.

In this paper, two important questions are addressed using the CIMS energy and emissions model:

1. What is the potential of CCS to contribute to national GHG abatement efforts?
2. What is the range of possible economic and emission outcomes?

On the first question, simulations suggest that CCS could contribute approximately 25% of all national reductions with carbon prices set at $100 per tonne, and upwards of 40% if reductions are aligned with the Government of Canada's *Turning the Corner* target of reducing emissions 20% below 2005 levels by 2020. Lastly, modeling indicates that as CCS costs rise, CCS continues to be deployed at high rates, but reductions are much less cost effective. That is, as CCS costs rise, there are still significant reductions from CCS, however the costs of a tonne abatement rises.

To address the second question, simulations for just Alberta were conducted to isolate the impacts of CCS on production costs. The simulations indicate that with CCS deployment roughly aligned with a $100 carbon price, the electricity sector in Alberta would have production cost increases in the order of 16% to 20%, and the petroleum crude sector would have increases of about 4% to 6%. This paper does not, however, investigate how these costs are distributed.

Despite the interesting results of the modeling exercise, it is important to note that the commercial application of CCS is hindered by a number of economic, social and environmental challenges. Strong investment by both the public and private sectors will be required to overcome the financial gap presented by CCS. However, plans for greater investment might face opposition from the interested public, including local landowners and environmental groups, and others who might resent public support for profitable entities in the electrical generating or oil industries. This is further complicated by the fact that much remains unknown about CCS technology and its potential impacts on health, safety and the environment. Some even question whether CCS is a case of "having your cake and eating it too" — a technology fix that delays the Canadian economy's transition to a cleaner, high tech development future. While not all these issues can be resolved in this short paper, it is clear that effective communication and stakeholder consultation will be needed to bridge this gap and to ensure the successful implementation of CCS projects. And clearly, any such consultation will only be possible if it is demonstrated and communicated that environmental concerns, either real or perceived, will be carefully addressed in the planning, implementation, monitoring and abandonment phases of CCS.

CCS technology will be a crucial element in the global transition to a low-carbon economy. Further development and implementation of CCS projects will require unprecedented collaboration as these processes will be trans-boundary, cross-jurisdictional and multi-sector. An opportunity exists for Canada to play a leading role in the development of technical expertise, regulatory approaches, and CCS products and services that will be required internationally. This will require investment, political will, and a deep understanding of both the urgency and severity of the climate change problem, and of the contribution that CCS technology can make to its mitigation.

1. Introduction: The Case for Carbon Capture and Storage

The main objective of this paper is to provide the context for CCS as part of Canada's long-term climate solution and to examine CCS potential in Canada. The paper first presents a series of emission forecasts and then compares these to the Government of Canada's GHG abatement targets. Next, the paper explores the potential role of CCS in achieving longer-term GHG reductions by asking three high level questions using the CIMS[1] energy and emissions model:

- Given foreseeable GHG abatement opportunities in sectors with CCS potential, what is the importance of CCS to overall abatement?
- What are the possible economic outcomes?
- What is the associated energy and emission penalty?

The paper then goes on to explore challenges to CCS deployment, including economic and environmental challenges that must be considered as this technology is further developed and applied.

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[1] Annex A provides an overview of CIMS.

2. Emission Forecast and GHG Abatement Targets in Canada

In this section, we present results of a national forecast of GHG emissions using the CIMS integrated economy, energy and emissions model, a business-as-usual (BAU) forecast.[2] The purpose of such modeling work is not, at least in this context, to predict or even recommend how Canada might best address climate change or the role CCS might play in this effort. Rather it is intended to draw out some interesting features and lessons to keep in mind when considering CCS as part of Canada's contribution to reducing GHG emissions.

Next, we simulate an economy-wide carbon price to achieve the Government of Canada's *Turning the Corner* reduction targets[3] (a climate policy case). While any number of policy levers will likely increase the rate of CCS deployment, such as regulations to reduce emissions from coal plants and oil and gas facilities using CCS, we choose to simulate the *Turning the Corner* targets given their long-term national focus.

The comparison of a BAU forecast with a policy case serves to illustrate the scale of CCS potential within the context of climate mitigation targets contemplated in Canada. We look at a less aggressive target, with lower carbon prices, in Section 3.0, where CCS potential is explored.

2.1 A GHG Forecast to 2050

With the economy growing at a rate of about 1.5% to 2% annually between now and 2050, economic activity can be expected to be 1.25 to 1.3 times greater in 2020 and 2.2 to 2.4 times greater in 2050. GHG emissions over the period grow correspondingly, but at a lower rate of about 1.2% annually due to an increased penetration over historical levels of energy efficiency and low emitting energy, to total just over 1,000 metric tonnes (MT) in 2050.[4] In the forecast, current shares of national emissions by region and sector more or less stay at current relative shares. The sectoral contribution to national emissions in the baseline forecast is provided in Table 1 and the regional breakdown is provided in Table 2.

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[2] In the past year alone, CIMS has been used by the federal government, National Round Table on the Environment and the Economy, Alberta, British Columbia, Saskatchewan and Manitoba to assess GHG policy options, and is currently being used by Ontario.

[3] We only address the targets in *Turning the Corner*, and, at least in our analysis in the front section, take into account the elaboration this past spring which calls for all oil sands facilities and coal plants to have CCS technologies in place starting in 2018.

[4] Using Informetrica 2007 long-run forecast to 2050, and EIA June 2008 energy forecast; and Canadian Association of Petroleum Producers (CAPP) 2007 Crude Oil forecast, markets and pipeline expansions.

Table 1. Distribution of Emissions by Sector

MT Carbon Dioxide Equivalent (CO2e) and Share (%) of National Total

	2010		2020		2030		2040		2050	
	MT	**%**	**MT**	**%**	**MT**	**%**	**MT**	**%**	**MT**	**%**
Residential	39	6%	40	5%	41	5%	40	4%	39	4%
Commercial	35	5%	41	5%	47	6%	56	6%	66	6%
Transportation	208	30%	253	31%	263	31%	282	31%	312	31%
Industrial Users	87	12%	91	11%	93	11%	102	11%	113	11%
Oil and Gas	157	23%	214	26%	217	26%	223	24%	230	23%
Electricity	123	18%	113	14%	119	14%	138	15%	170	17%
Other	49	7%	57	7%	65	8%	73	8%	82	8%
Total MT CO2e	**698***		**807**		**845**		**915**		**1,012**	

* Does not include agroecosystems.

Source: CIMS Modelling, 2008

Table 2. Distribution of Emissions by Region

MT CO2e and Share (%) of National Total

	2010		2020		2030		2040		2050	
	MT	**%**	**MT**	**%**	**MT**	**%**	**MT**	**%**	**MT**	**%**
British Columbia	66	10%	79	10%	82	10%	89	10%	97	10%
Alberta	239	34%	312	39%	327	39%	346	38%	371	37%
Saskatchewan	51	7%	48	6%	46	5%	47	5%	51	5%
Manitoba	12	2%	12	1%	11	1%	11	1%	11	1%
Ontario	194	28%	214	26%	242	29%	282	31%	332	33%
Quebec	84	12%	90	11%	90	11%	93	10%	99	10%
Atlantic	51	7%	52	6%	47	6%	47	5%	50	5%
Total MT CO2e	**698**		**807**		**845**		**915**		**1,012**	

Source: CIMS Modelling, 2008

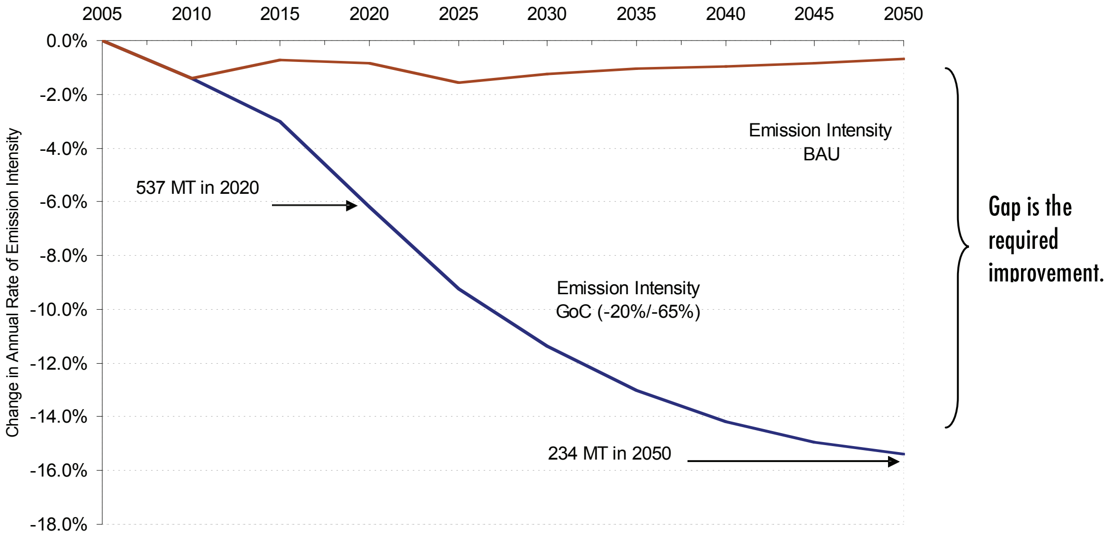
2.2 The Policy Case: Deep National Reductions in 2020 and 2050

The carbon policy case runs a set of national carbon prices in time at a level that achieves the *Turning the Corner* targets of 20% below current levels in 2020 and 65% below current levels in

2050. To achieve reductions of this magnitude, carbon prices in CIMS need to climb to $100 in 2020 and to $300[5] in 2030 through 2050. The associated pace of reductions requires a decoupling of economic activity and emissions equivalent to approximately a seven-fold drop from the BAU in 2020 and a 22-fold drop in 2050 (Figure 1). That is, the economy still grows significantly but emissions fall rapidly due to abatement from CCS, output reductions, fuel switching and energy efficiency (we discuss assumed CCS costs and penetration in Section 3 below). Figure 1 provides the emission intensity (emissions/GDP) under the BAU and the policy cases, and shows a pace of emission intensity reductions under the policy case that is significant.

Figure 1. Annual Rate of Emission Intensity (Emissions/GDP)

BAU and Government of Canada (GoC) -20%/-65% Targets



In Table 3 we present the pace of reductions required for a number of sectors under the forecast BAU and policy cases. For sectors with CCS potential, notably oil and gas, electricity and the large final emitters, emission intensities must fall substantially from forecast BAU levels to achieve the *Turning the Corner* targets. The oil and gas sector, for example, would need to reduce emission intensities in the order of 7% annually by 2020 and 14% by 2050 (i.e. the net reduction is BAU minus the target improvement).

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[5] In this section we assume unilateral or domestic actions alone in meeting the governments' target. We relax this assumption later in this paper, and look at a more flexible policy scenario.

Table 3. Annual Emission Intensity in BAU and for GoC Targets

CCS Sectors and the Rest of the Economy

	2010	2020	2030	2040	2050
	BAU Annual Emission Intensity Change				
Oil and Gas	0.9%	0.9%	-0.2%	-0.9%	-1.3%
Electricity	-2.5%	-2.3%	-0.6%	-0.3%	0.4%
Other Large Emitters	-0.1%	-0.9%	-1.3%	-1.3%	-1.1%
Rest of Economy	-1.7%	-0.4%	-1.4%	-1.0%	-0.9%
	Target Improvement for -20% in 2020 and -65% in 2050				
Net Intensity Improvement Given Carbon Price	-1.4%	-6.2%	-11.4%	-14.2%	-15.4%

Source: CIMS Modelling and Informetrica Summary of Long-Range Economic Forecasts, 2008

With the scale of the challenge defined, the next section provides an overview of the mitigation potential of CCS.

3. The Potential for GHG Reductions in Canada from CCS Technology

While CCS can play an important role in climate change mitigation, much remains unknown about CCS, including its potential to deliver GHG emission reductions, and the associated economic and environmental costs. In an attempt to fill this knowledge gap and to better understand CCS's potential contribution in Canada, CIMS was used to simulate a number of scenarios that explore CCS emission reductions potential across a range of CCS costs. In the simulations, we set aside questions of technical feasibility and instead focus on the relative cost of CCS versus other abatement choices. This is reasonable, as most observers believe the challenges with CCS deployment are not technical, but primarily commercial — it can be done, the question is at what cost will we achieve what level of technical success. We did not, however, compete CCS with nuclear power in the simulations, which the reader can judge to be a prudent assumption or not.

We conducted modelling in three key areas:

- Given foreseeable GHG abatement opportunities in sectors with CCS potential, what is the importance of CCS to overall abatement?
- What are the possible economic outcomes?
- What is the associated energy and emission penalty?

Before addressing these three questions, it is important to define where CCS is applied and at what cost in the simulations.

3.1 CCS Applicability and Costs

CCS is most cost effective for emission sources and industries with relatively pure streams of carbon dioxide (CO_2), such as natural gas production, ammonia production in chemical manufacturing, and hydrogen production in oil sands upgrading. These are the lowest cost options in the CIMS model. For other emissions sources, such as electric utilities, oil sands upgrader furnaces, oil sands in-situ operations and other industrial sources, costs are significantly higher, indicating CCS supply costs rise with deployment outside of sources with relatively pure CO_2 streams. That is to say, more energy and cost is required to separate CO_2 from other gases.

In CIMS, the IPCC CCS costs are adopted as the base case technology cost. Table 4 presents a snapshot of the IPCC costs in two applications, with a range of about \$20 to \$70 per tonne removed. We also observe that these costs are likely understated, especially in the near term as cost estimates have consistently escalated over the past three years. Given this trend, CIMS includes rapidly increasing CCS costs, starting from the lowest cost options, such as natural gas processing and hydrogen production, and rising to \$200 per tonne removed for many of the emission sources, such as boilers, furnaces, and Steam Assisted Gravity Drainage (SAGD) facilities. That is, there is a rapidly increasing CCS supply curve in CIMS. While we use the IPCC costs as a base, we conduct sensitivity tests that vary all CCS costs upwards. These sensitivity cases are discussed below. Note also that CIMS does account for a decreasing cost in time as more CCS is deployed, which implies that with more CCS deployment in early periods, CCS costs fall faster in later periods.

Table 4. Estimated Cost of Capturing, Transporting and Storing CO_2 From Selected Sources

Power Plant Type	**Cost of capturing CO_2 (2005$ CDN / tonne CO_2e)**		
	Low	**Medium**	**High**
Pulverized Coal	23	41	66
Integrated Gasification Combined Cycle	17	30	48

Note: These values were informed by the IPCC's Special Report on Carbon Dioxide Capture and Storage, 2005.

3.2 The Importance of CCS to National Abatement

This section identifies a range of national emission reduction potential assuming CCS is technically feasible. We first simulate an "upper potential scenario" that applies the carbon prices required to achieve the *Turning the Corner* targets and then simulate a "practical potential" scenario with carbon prices capped at $100 per tonne of CO_2e removed or abated.

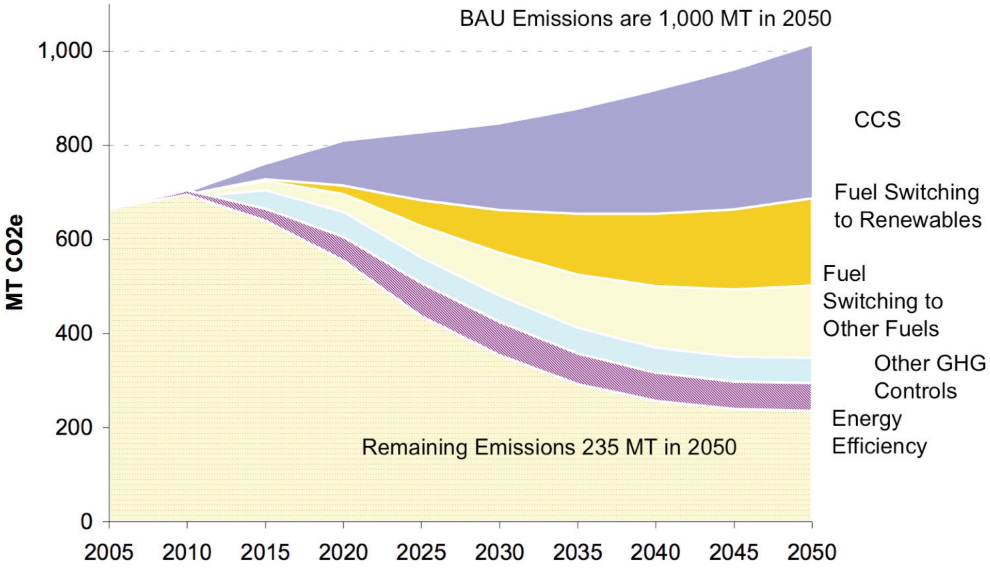
A CCS Upper Potential: *Turning the Corner* Targets

To achieve the Government of Canada's emission reduction targets identified in *Turning the Corner* (20% below current levels in 2020 and 65% below current levels in 2050) our modelling indicates that economy-wide carbon prices need to climb to $115 in 2020 and to $300 by 2050. With carbon prices at this level, CCS becomes widely deployed in the simulation given the range of prices identified above ($20 to $200) and the relative cost and supply potential of other abatement opportunities. Indeed, given the depth of the proposed targets, CCS is the predominant abatement choice in chemicals, electricity generation, oil sands, and in some cases, cement.

Figure 2 provides a snapshot of the major sources of abatement where economy-wide carbon prices were simulated and the sources of abatement identified. CCS accounts for an increasing share of total abatement below the BAU, contributing from 35% to 40% of all abatement in 2020 to over 40% in 2050. While nuclear could become cost competitive in some applications at the carbon prices we simulated, because widespread nuclear deployment raises political questions beyond its relative cost, we excluded nuclear to focus on the CCS potential. Energy efficiency, even at these carbon prices, doesn't seem to deliver the scale of reductions required, whereas fuel switching becomes relatively costly fast, and therefore its abatement potential is limited.

Figure 2. Major Sources of National Abatement

Government of Canada *Turning the Corner* Targets

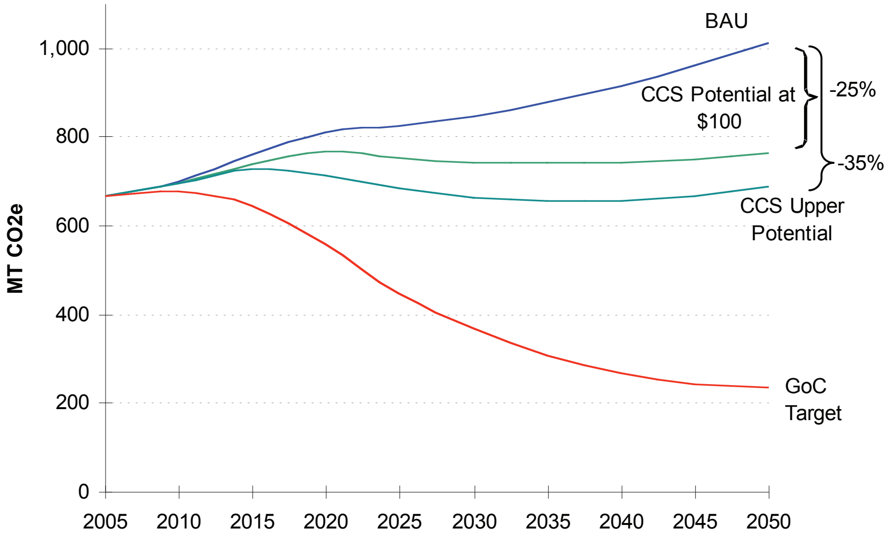


A Practical Potential Scenario: Carbon Price Capped at $100 per Tonne

We also modeled a scenario that caps emission prices at $100, reflecting a maximum policy flexibility scenario with access to lower cost reductions in North America, internationally or through some sort of capped financial obligation (e.g. Technology Fund). In Figure 3, with a carbon price of $100 per tonne, CCS in the simulation contributes in the order of 25% of the GoC target, or about 45 MT in 2020 and 251 MT in 2050. This compares with an upper potential scenario of about 35% to 40% when carbon prices are in the range of $300 in 2030 and beyond.

Figure 3. CCS Potential Relative to BAU and Government of Canada Targets

Upper Potential ($300/Tonne in 2050) and Potential at $100/Tonne Carbon Price



In the case of a carbon price at $100, the CCS supply is still significant at about 25% of all national reductions in 2050. But with a carbon price that is three times as high, rising from $100 to $300 in 2050, the incremental addition to abatement is only 10%.[6] Figure 2 shows that at the latter price, fuel switching to other fuels (e.g. natural gas) will play a significant role in meeting targets. This translates into a tripling of the carbon cost (from $100 to $300) for a 40% increase in emission reductions (from 25% to 35%).

This finding highlights the rapidly increasing supply cost of CCS as more marginal sources abate in response to higher carbon prices (or a regulatory requirement). We interpret this to mean that CCS supply may be relatively insensitive to a rapidly increasing carbon price. Given the importance of this observation and its foundation in the costs we assumed in the simulation, we conducted a series of simulations to test the sensitivity of CCS supply to an increasing CCS supply cost, while holding the carbon price fixed.

3.3 CCS Cost Sensitivity Assessment

An increasing CCS supply cost was simulated for those sectors with significant CCS potential: electrical generation, petroleum refining, oil and gas extraction, cement and chemicals. These sectors account for approximately 50% of Canada's GHG emissions in any given BAU year. Three cost sensitivity runs were conducted with the IPCC costs increased two, three and four times, and one run with CCS unavailable. In all cases, a $100 sector-wide carbon price was

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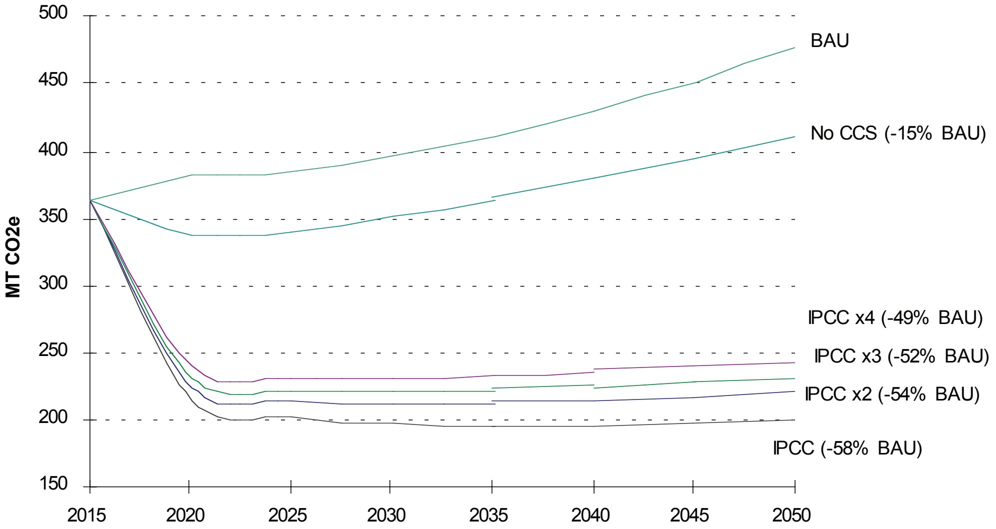
[6] CIMS captures relative abatement price changes in time through a declining cost function. This means that as more CCS or any abatement choice is brought on early in simulation periods, future costs of that technology drop faster relative to other technologies.

simulated so that emission reduction potentials could be tracked. Figure 4 provides the results of alternative cost assumptions.

Figure 4. Impact of Alternative CCS Cost Assumptions on Emissions with a $100 Carbon Price

Electricity, Oil and Gas, and Chemicals



Five observations are apparent from the simulations:

- **Energy efficiency and the adoption of renewable energy can't deliver the magnitude of the abatement potential of CCS, and the greater or more stringent the target, the greater the feasibility of this assertion.** If CCS were unavailable, significantly less emissions would be reduced at the emissions price simulated for this analysis. In the scenario where CCS is unavailable, the energy supply and industrial sectors only reduce emissions by 15% below the reference case throughout the simulation, in comparison to 35% to 40% below the reference projection when CCS is available. Emissions reductions from improvements to energy efficiency and fuel switching account for most reductions when CCS is not available, but their potential is low in comparison. Ironically, it is our conclusion that early and effective penetration of renewables and energy efficiency is most "doable" under moderate target scenarios. The more stringent the target, the greater the need for much larger infrastructure investments, like CCS or even nuclear power and hydro. So in effect, renewable and energy efficiency are not so much "crowded out" by particular technologies as by aggressive targets. Whether or not the magnitude of this effect is correct, the key observation is that the potential of these alternatives is limited relative to CCS.

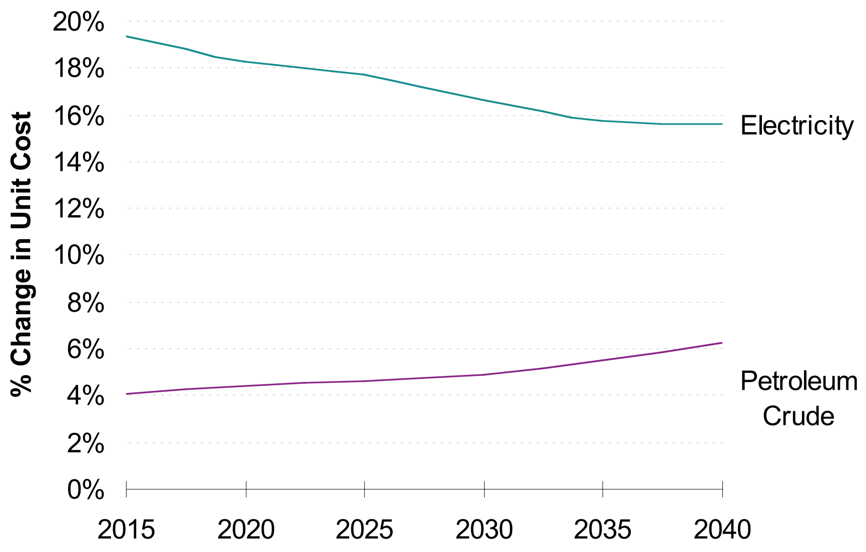
- **Emission reductions from CCS are somewhat insensitive to cost increases.** As CCS costs rise with carbon prices constant around $100, supply of CO_2 reductions from CCS shrinks but not significantly. Even when costs are four times higher than the IPCC estimates (an average of about $200 per tonne of abatement supplied), CCS still supplies significant reductions, although the penetration of energy efficiency and renewables is increased. Therefore, as CCS costs rise, CCS deployment is still significant and drives down emissions, albeit at lower rates.
- **At very high CCS costs, nuclear energy could become a viable option.** While the applicability of nuclear generation was limited in the simulations, cost comparisons show that nuclear becomes cost competitive at high CCS costs. At some cost point, therefore, simulations that enable more nuclear penetration would likely serve as a backstop to some of the high CCS applications. Beyond the medium-term (out to 2050) in oil sands applications (SAGD and upgrading), this is particularly true where electricity applications can be substituted for retired fossil fuel capital stock.
- **With higher CCS costs, firms may choose to reduce output in the covered or regulated jurisdiction as a way of meeting compliance targets.** Firms may choose to meet binding constraints by reducing output, or deferring expansions of the base activity, particularly if it is more cost effective to do so. As CCS costs rise, the relative price of abatement choices changes. As we increased the CCS supply cost, an increasing share of abatement was supplied through decreased output instead of CCS. If this was the case, higher leakage to non-regulated jurisdictions (i.e. outside of Canada) in both investment and emissions might be expected as production or imports increased in countries without carbon constraints.
- **As CCS costs rise under a binding emission constraint, total abatement costs rise proportionally due to a lack of abatement substitutes.** A related point is that to achieve the same target, such as an intensity standard in the face of climbing CCS costs, the overall cost of abatement rises in proportion to the rising CCS costs. That is, abatement substitutes are not really available at the deep target levels, and therefore total abatement costs can only rise as CCS costs rise.

3.4 Possible Economic Outcomes

In order to highlight the potential impact on production costs of increased CCS penetration, a simulation was conducted of a $100 carbon price in Alberta. The benefit of this focus is obvious given both the high emission intensity of energy producers in the province as well as the CCS potential. Figure 5 illustrates the cost impact assuming a $100 carbon price and the IPCC CCS costs. We focus on electricity and petroleum crude sectors in Alberta since most, if not all, reductions in the simulation come from CCS, which serves to isolate the CCS cost impact relative to other abatement choices.

As shown in Figure 5, in the electricity generation sector, the production cost increase from CCS ranges between 16% and 20% in the simulation, but is considerably lower in the petroleum crude sector, where it ranges between 4% and 6%. Higher CCS costs (two times, etc.) were not simulated in this example since costs — but not emissions — were fixed, and therefore higher CCS costs would simply lead to less reductions (and less CCS deployment) for the given carbon price.

Figure 5. Impact on Unit Production Costs in Electricity and Petroleum Crude, Alberta



3.5 Associated Energy and Emission Increases

CCS requires a significant amount of energy to capture and then pump the emissions for storage. As a result of this energy use, the reduced emissions are somewhat offset by a penalty in the form of subsequent emissions. The energy penalty for various types of plants as identified by the IPCC is provided below in Table 4. GHG emissions removal efficiency by CCS in an NGCC example is approximately 86%, with an energy penalty of approximately 15%, leading to a maximum net removal efficiency of CO_2 of approximately 73%.

Table 5. IPCC Cost Estimates for CCS

Plant Type	Fuel Type	Percent CO_2 Reduction	CCS Energy Use	Percent NO_X Reduction
Natural Gas Combined Cycle (NGCC)	Natural Gas	86%	15%	-22%
Pulverized Coal (PC)	Coal	85%	25%	-31%
Integrated Gasification Combined Cycle (IGCC)	Various	86%	23%	-11%
Hydrogen	Natural Gas	86%	0%	0%

Source: IPCC Special Report on Carbon Dioxide Capture and Storage

In CIMS this energy penalty is modeled as an emissions penalty based on the fuel profiles of the process units and the energy required for CCS capture and transmission. With a $100 carbon price applied to Alberta's electricity and upstream oil and gas sectors, about 7% to 12% of all reductions from CCS are not achieved due to the energy penalty in any given simulation period.

A further outcome worth mentioning is that the energy penalty from CCS could come at the expense of energy efficiency. In the early periods of the model and with a carbon price in effect, CCS is not available and energy efficiency improves in time due to the deployment of less emission-intensive capital stock. As CCS is brought on in the simulation, the increased energy for CCS either offsets or reduces the level of energy efficiency that is in place. This is numerically accounted for by discounting the actual tons of CO_2 reduction from CCS by the amount of the emissions penalty, resulting in what is called CO_2 abated rather than CO_2 captured.

4. The Challenges of CCS in Canada

Interest in CCS technology has increased in recent years in Canada and internationally. Yet the development and application of the technology faces a number of challenges. In particular, CCS represents a relatively new approach to climate change mitigation, and few concrete examples of its success or failure exist to date. Much remains unknown about the science of CCS, its economic feasibility and its environmental and social impacts. The next section attempts to address these challenges and knowledge gaps.

4.1 Economic Challenges

One of the greatest challenges to CCS development and application in Canada is the financial gap between the "with CCS" and "without CCS" project scenarios. The EcoEnergy CCS Task Force report (2008) estimates that the initial capital investment required for the first industrial CCS installations in Canada could be in the order of hundreds of millions of dollars.

These initial CCS costs and the associated economic risks can be partly mitigated by reducing the compliance costs associated with current and future GHG regulations in Canada. Committing $2 billion of public investment in CCS to spur innovation and reduce infrastructure costs, as suggested by the CCS Task Force (2008), is a good start. But it is only a start, since the estimated 5 MT of reductions that may result is but a small share of the total reductions contemplated by many Canadian jurisdictions.

In this context, Canada will need to emerge as a global leader in the CCS field by increasing support for research and development, and facilitating the development of both human and technical capital. Leveraging current experience in the oil and gas industry will be critical, as will improving understanding of CO_2 pipeline activity to address risks, which are similar to those faced in the natural gas sector (CCS Task Force, 2008). Therefore CCS offers Canada an opportunity to build on its existing energy infrastructure and its fossil energy endowment while managing the associated GHG emissions (CCS Task Force, 2008).

Indeed, Canada's experience in engineering and in the energy sector can help the country become a pioneer and leading international player in CCS. To illustrate, the Weyburn-Midale CO_2 Project in southeastern Saskatchewan is the world's first CO_2 measuring, monitoring and verification project in CCS. This project has provided Canada with extensive first-hand knowledge about CO_2 capture and storage during its first (2000–2005) and second (2005–2011) implementation phases. Future projects can learn from and build on this experience, particularly in aspects such as direct storage into saline aquifers and injection to revive oil production.

When considering the economic challenges associated with CCS, it is important to distinguish between CCS for coal and CCS for oil, and to consider the different politics and economics related to each. More specifically, CCS for coal is a more globally shared issue, with major developing economies such as China and India playing key roles. CCS for oil — particularly oil sands — is much more important for, and applicable to, the Canadian context. An understanding of these "geographically based" priorities needs to be in place, and countries such as Canada and Venezuela should play a leading role in the development of CCS for oil. There are also "sector based" considerations that must be taken into account. For instance, investment in CCS might be more affordable for the oil sector than for other sectors, such as the utilities, particularly as their supply becomes increasingly liberalized. This may be countered by the ability of power utilities to distribute the CCS costs of a specific plant more broadly across the rate payers through a pool price mechanism. An understanding of these issues needs to be in place in order to properly address the challenges associated with CCS.

As mentioned previously, a key challenge to CCS development and implementation is financing. The European Commission (2008) estimates that at current technology prices, the up-front investment costs for plants with CCS are approximately 30% to 70% greater than the cost for plants without CCS. However, the IPCC (2005) states that over the next decade these costs should be reduced by approximately 20% to 30%, as new technologies become available and as learning by doing and innovation decrease deployment costs. Despite this, critics of CCS argue that investments in this sector will serve to decrease investments in renewable energy, energy efficiency, and other areas that the Canadian Government should focus on to combat climate change. While this may be the case, these options perhaps provide a limited opportunity for reductions relative to the emissions in major industrial sectors like electricity generation and oil and gas extraction.

CCS financing, however, must be addressed within a broader policy context. In Canada, it must be addressed within the regulatory framework provided in *Turning the Corner*, or through the appropriate provincial regulations if an equivalency arrangement between federal and provincial climate regulations is achieved. More specifically, the federal report calls for CCS-level targets to be applied in Canada by 2018 — dictating a need for greater public financial investment to meet the stated goal. It is therefore important that a broad policy framework include CCS financing mechanisms, and allow for it to be addressed in the context of regulatory markets and carbon prices, thus stimulating the creation of incentives for CCS financing through carbon market mechanisms or other means.

It is also important to consider the urgency inherent to greater CCS public investment. Many Canadian electricity plants are reaching retirement, and if the government fails to demonstrate that it is serious about CCS, new plants will be built with conventional technology, rendering them more costly to retrofit with CCS in the long-run (CCS Task Force, 2008). Similarly, oil sands facilities are expected to undergo dramatic growth in the next decade. If proper incentives for CCS are not in place, these facilities could be built conventionally with a resultant high conversion cost or "locked in GHG emissions profile" over their 40 year life spans.

Given the above, it follows that the evolving regulatory environment at the national and provincial levels in Canada can be a driving force for further CCS development and implementation. There are other important, non-Canadian drivers to consider as well, such as the U.S. Energy Independence and Security Act of 2007, which sets new procurement rules on fuel standards. These standards are aimed at reducing U.S. dependency on petroleum and promoting the sale of "cleaner" fuels (White House press release, 2007). Since the U.S. is a primary purchaser of Canadian oil, U.S. regulations could influence the development of stricter environmental standards in the Canadian oil sector. This highlights the important role that CCS technology can play in oil production, particularly in the Canadian oil sands.

4.2 Social Challenges

Societal acceptance is an essential aspect of the diffusion and application of new technologies, and must be considered in the case of CCS. Public perception of risks associated with CCS may arise due to concerns about the untested nature of sequestration technology, and potential long-term environmental and safety impacts. Also, carbon sequestration may be viewed as a disincentive to reducing GHG emissions at the source, or as a means of enabling industry to continue to consuming energy and emitting greenhouse gases at current rates.

The last point is of particular importance. The government of Alberta's recent proposal to invest \$2 billion in a CCS project in that province was criticized, with some suggesting that the funds could be better used for health care, education or to address homelessness. The project is also targeted in the latest provincial auditor general's report, which questions the cost effectiveness of the government's climate change plan and accuses it of failing to clarify how emission reduction targets will be met.

For some stakeholders, the life cycle valuation of CO_2 capture, compression, transportation and storage brings into question its effectiveness as a mitigation tool. Proponents will have to clearly demonstrate the net benefit, and be careful not to portray CCS as a panacea for climate change. It is also important to consider that while public acceptance will influence the deployment of CCS technology, public understanding of it is limited, particularly because of the limited number of existing projects. In this context, it is important to mention that since environmental non-governmental organizations (ENGOs) tend to play a large role in shaping the public debate on environmental issues, it can be expected that their support of CCS or lack thereof may influence the ultimate level of public acceptance. Given that ENGOs currently have varied levels of acceptance for CCS, public confusion could arise.

A review of the implementation of other projects in Canadian communities, such as nuclear waste disposal sites in Ontario and coal bed development in Southern Alberta, reveals useful lessons to consider regarding the NIMBY (not in my backyard) syndrome sometimes associated with environmental projects. Lessons learned from these activities suggest that NIMBY can be avoided by delivering the right information in the right way, and by communicating project benefits to local residents and society as a whole. In the case of CCS, the link with climate change mitigation must play a leading role.

Many of the areas in Canada that are amenable to CCS have a regional history of oil and gas activities. Stakeholder familiarity with the oil and gas industry and practices like high pressure pipelining, drilling and well operations will likely benefit CCS proponents in most cases. However, poor communication by previous oil and gas proponents or current CCS proponents can lead to negative opinions that will be difficult, if not impossible, to alter. Adverse public perception of CCS and the additional time and effort required to address stakeholder concerns will add costs to CCS projects and delay implementation. It is also evident that a single incident (such as a pipeline rupture or wellbore CO_2 leak) early in the life of this new technology could dramatically alter public receptiveness to CCS — even if the actual outcome of the event is benign, it will call into question the credibility of proponents' claims about the safety of CCS.

It is therefore imperative to create a dialogue to increase public knowledge of CCS, and to discuss the risks and benefits associated with it. Communication strategies must address the specific needs of local communities, particularly in areas where there has been little oil and gas activity, where oil and gas activity has resulted in strained community relations, or where First Nations communities exist. Unless this technology is well understood and accepted as a safe and sound option for CO_2 abatement, it runs the risk of being dismissed as way to avoid dealing with our current carbon emission patterns, and passing the problem on to future generations.

4.3 Environmental Challenges

The environmental risks associated with CCS can be categorized as local risks — effects caused by high, localized concentrations of CO_2 resulting from leakage; and global risks — effects on the global climate due to low-level CO_2 leaked back into the atmosphere over the longer term. One of the major and most serious environmental challenges posed at the local level is water contamination. The IPCC report (2005) on CCS outlines the risk of water contamination due to leakage of an injection well. Whether the failure is immediate through a major structural failure of the carbon well, or over time due to an undetected geologic fault allowing the CO_2 to migrate into water zones, the elevated CO_2 levels could contaminate groundwater and underground aquifers near the leakage.

Such contamination of a water supply would have a secondary impact on aquatic plant life and any other life forms that use the groundwater, or aquifer, as a source of drinking water. In concentrated exposure, such CO_2 contamination can be lethal to plant and animal life. Remedial measures are available, but intercepting CO_2 leakage prior to aquifer contamination is essential. Once contamination occurs, techniques for contamination removal are very expensive (IPCC, 2005).

IPCC studies (2005) have previously shown that when exposure to high concentrations of CO_2 has been sustained by ocean organisms, mortality occurs and the overall ocean ecosystem is impacted. Impacts measured on marine life include "reduced rate of calcification, reproduction, growth, circulatory oxygen supply and mobility".

Leakage of CO_2 to the atmosphere can also have significant negative impacts on local life forms. As in water contamination, leakage could arise from an injection well, or from a major structural failure that would lead to an immediate release of a high concentration of CO_2 into the atmosphere.

Many of the risks typically associated with infrastructure projects are well understood and are routinely addressed through compliance with applicable standards and regulations, sound engineering and design, proper planning, use of proven technologies, and application of best practices. Ensuring the protection of local aquifers, and the structural integrity of carbon injection sites, must be an integral component of CCS projects. This applies to the planning and operation phases of projects, as well to abandonment procedures, which must ensure that abandoned wells are not susceptible to failure after their usage period and that human health is not affected as a result.

The risks associated specifically with CO_2 can be mitigated in part by adopting technologies proven in other applications, by applying expertise and knowledge gained from these other areas as well as from carbon sequestration pilots and current research and development, and by selecting appropriate site(s) for project infrastructure. Successful completion of early projects will contribute to addressing some of the challenges to further full-scale carbon sequestration by providing information to governments to support regulatory and policy decision-making; by encouraging investment and take-up by industry as reliability and economics are proven; and by increasing public buy-in as the safety and effectiveness of the technology is demonstrated and communicated.

5. Conclusion

CCS is likely to be an important technology that will help meet GHG emission reduction targets internationally. In Canada, due to the structure of the national economy and its heavy reliance on the energy sector, CCS technology could play a key role in helping the country meet its energy needs while addressing its emission reduction targets. Canada must view CCS development as a national responsibility that should start in Western Canada, where the oil and gas industries are already actively pursuing CCS as a GHG mitigation approach. CCS can then eventually be applied across the country and around the globe.

The modelling and analysis presented in this paper attempted to address 1) the potential of CCS to contribute to overall GHG abatement, and 2) the associated economic outcomes and energy and emissions penalty. With respect to the first question, modeling results indicate that in order to achieve Canada's current GHG emission target of 20% below current levels by 2020, economy-wide carbon prices would need to climb to $115 in 2020, $225 in 2020 and $300 in 2050. With carbon prices at this level, CCS would be widely deployed. When carbon prices are capped at $100, however, the simulation indicates that CCS could contribute approximately 25% of the emission reductions required to meet Canadian targets. Lastly, modelling indicates that as carbon prices fall, CCS continues to be dominant, but as carbon prices rise from $100 to $300 per tonne, reductions can be achieved from CCS but at a lower cost-effectiveness.

In addressing the second question, simulations for just Alberta were conducted to isolate the impacts of CCS on production costs. The simulations indicate that with CCS deployment roughly aligned with a $100 carbon price, the electricity sector in Alberta would have production cost increases of approximately 16% to 20% and the petroleum crude sector would have increases of about 4% to 6%. CCS-associated production costs are significantly higher in electricity than petroleum, as the total energy input and emissions relative to total production costs are higher in that sector.

When considering the energy penalty associated with CCS, the modeling exercise indicates that economy-wide energy efficiency is reduced with more CCS deployment as CCS itself is a significant energy user.

Despite the interesting results of the modeling exercise, it is important to note that commercial application of CCS is hindered by a number of economic, social and environmental challenges. Strong investment by both the public and private sectors will be required to overcome the financial gap presented by CCS. However, plans for greater investment might face opposition from the public and from ENGOs, particularly since much remains unknown about this technology, and there may be resistance to public funding for an "industrial solution." Effective communication and stakeholder consultation is needed to address this potential opposition and to ensure the successful implementation of CCS projects. Finally, environmental considerations must be carefully addressed in the planning, implementation, monitoring and abandonment phases of all CCS projects, and the safety of the technology must be effectively demonstrated and communicated.

CCS technology will be of growing importance as countries strive to transition to a low-carbon economy. Further development and implementation of CCS projects will require unprecedented collaboration as these processes will be trans-boundary, cross-jurisdictional and multi-sector. An opportunity exists for Canada to play a leading role in the development of technical expertise, regulatory approaches, and CCS products and services that will be required internationally. This will require investment, political will and a deep understanding of both the urgency and severity of the climate change problem, and of the contributions that CCS technology can make to its mitigation.

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Annex A: Description of the CIMS Model

CIMS has a detailed representation of technologies that produce goods and services throughout the economy and attempts to simulate capital stock turnover and choice between these technologies realistically. It also includes a representation of equilibrium feedbacks, such that supply and demand for energy intensive goods and services adjusts to reflect policy.

Model Structure and Simulation of Capital Stock Turnover

As a technology vintage model, CIMS tracks the evolution of capital stocks over time through retirements, retrofits and new purchases, in which consumers and businesses make sequential acquisitions with limited foresight about the future. This is particularly important for understanding the implications of alternative time paths for emissions reductions. The model calculates energy costs (and emissions) for each energy service in the economy, such as heated commercial floor space or person kilometres traveled. In each time period, capital stocks are retired according to an age-dependent function (although retrofit of un-retired stocks is possible if warranted by changing economic conditions), and demand for new stocks grows or declines depending on the initial exogenous forecast of economic output, and the subsequent interplay of energy supply–demand with the macroeconomic module. A model simulation iterates between energy supply–demand and the macroeconomic module until energy price changes fall below a threshold value, and repeats this convergence procedure in each subsequent five-year period of a complete run.

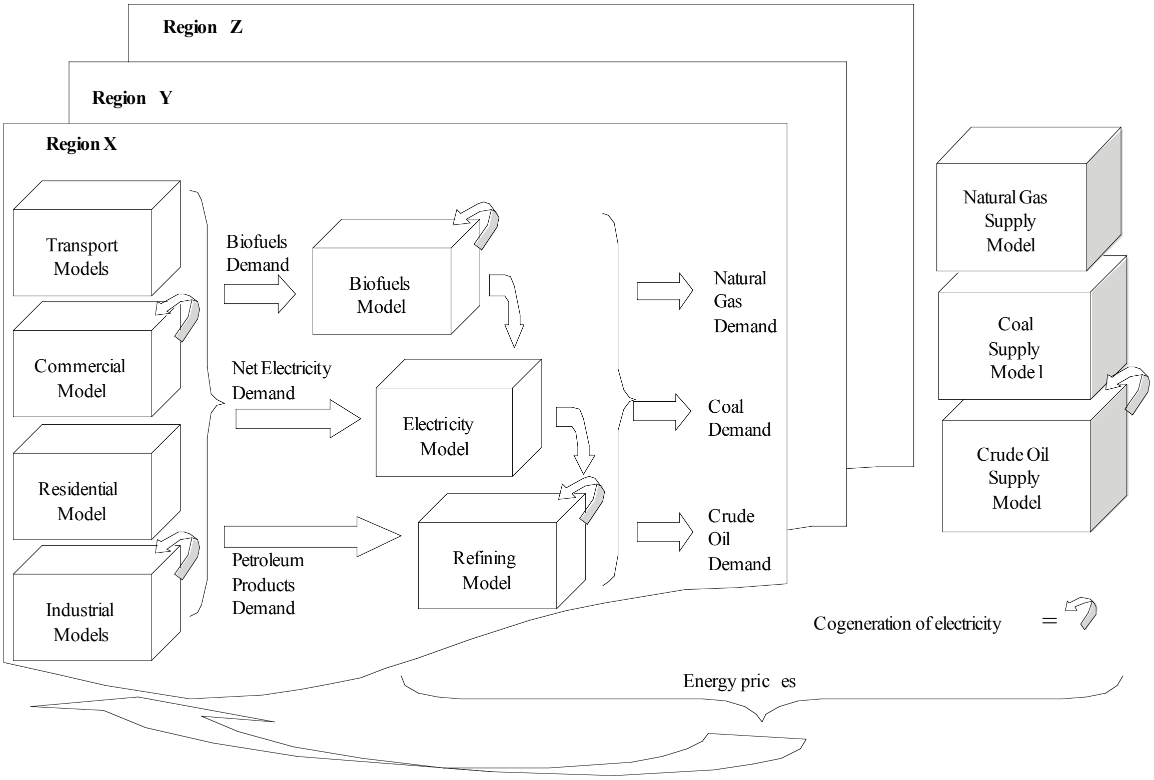
CIMS simulates the competition of technologies at each energy service node in the economy based on a comparison of their life cycle cost (LCC) and some technology-specific controls, such as a maximum market share limit in the cases where a technology is constrained by physical, technical or regulatory means from capturing all of a market. Instead of basing its simulation of technology choices only on financial costs and social discount rates, CIMS applies a definition of LCC that differs from that of bottom-up analysis by including intangible costs that reflect consumer and business preferences and the implicit discount rates revealed by real-world technology acquisition behaviour.

Equilibrium Feedbacks in CIMS

CIMS is an integrated, energy-economy equilibrium model that simulates the interaction of energy supply-demand and the macroeconomic performance of key sectors of the economy, including trade effects. Unlike most computable general equilibrium models, however, the current version of CIMS does not equilibrate government budgets and the markets for employment and investment. Also, its representation of the economy's inputs and outputs is skewed toward energy supply, energy intensive industries, and key energy end-uses in the residential, commercial/institutional and transportation sectors.

CIMS estimates the effect of a policy by comparing a business-as-usual forecast to one where the policy is added to the simulation. The model solves for the policy effect in two phases in each run period. In the first phase, an energy policy (e.g., ranging from a national emissions price to a technology specific constraint or subsidy, or some combination thereof) is first applied to the final goods and services production side of the economy, where goods and services producers and consumers choose capital stocks based on CIMS' technological choice functions. Based on this initial run, the model then calculates the demand for electricity, refined petroleum products and primary energy commodities, and calculates their cost of production. If the price of any of these commodities has changed by a threshold amount from the business-as-usual case, then supply and demand are considered to be out of equilibrium, and the model is re-run based on prices calculated from the new costs of production. The model will re-run until a new equilibrium set of energy prices and demands is reached. The figure below provides a schematic of this process.

CIMS Energy Supply and Demand Flow Model



In the second phase, once a new set of energy prices and demands under policy has been found, the model measures how the cost of producing traded goods and services has changed given the new energy prices and other effects of the policy. For internationally traded goods, such as lumber and passenger vehicles, CIMS adjusts demand using price elasticities that provide a long-run demand response that blends domestic and international demand for these goods (the "Armington" specification).[7] If demand for any good or service has shifted more than a threshold

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[7] CIMS' Armington elasticities are econometrically estimated from 1960–1990 data. If price changes fall outside of these historic ranges, the elasticities offer less certainty.

amount, supply and demand are considered to be out of balance and the model re-runs using these new demands. The model continues re-running until both energy and goods and services supply and demand come into balance, and repeats this balancing procedure in each subsequent five-year period of a complete run.

Empirical Basis of Parameter Values

Technical and market literature provide the conventional bottom-up data on the costs and energy efficiency of new technologies. Because there are few detailed surveys of the annual energy consumption of the individual capital stocks tracked by the model (especially smaller units), these must be estimated from surveys at different levels of technological detail and by calibrating the model's simulated energy consumption to real-world aggregate data for a base year.

Fuel-based GHG emissions are calculated directly from CIMS' estimates of fuel consumption and the GHG coefficient of the fuel type. Process-based GHG emissions are estimated based on technological performance or chemical stoichiometric proportions. CIMS tracks the emissions of all types of GHGs, and reports these emissions in terms of carbon dioxide equivalents.[8] Estimation of behavioural parameters is done through a combination of literature review, judgment and meta-analysis, supplemented with the use of discrete choice surveys for estimating models whose parameters can be transposed into behavioural parameters in CIMS.

Simulating Endogenous Technological Change with CIMS

CIMS includes two functions for simulating endogenous change in individual technologies' characteristics in response to policy: a declining capital cost function and a declining intangible cost function. The declining capital cost function links a technology's financial cost in future periods to its cumulative production, reflecting economies-of-learning and scale (e.g., the observed decline in the cost of wind turbines as their global cumulative production has risen). The declining capital cost function is composed of two additive components: one that captures Canadian cumulative production and one that captures global cumulative production. The declining intangible cost function links the intangible costs of a technology in a given period with its market share in the previous period, reflecting improved availability of information and decreased perceptions of risk as new technologies become increasingly integrated into the wider economy (e.g., the "champion effect" in markets for new technologies); if a popular and well respected community member adopts a new technology, the rest of the community becomes more likely to adopt the technology.

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[8] CIMS uses the 2001 100-year global warming potential estimates from Intergovernmental Panel on Climate Change, 2001, *Climate Change 2001: The Scientific Basis*, Cambridge, UK, Cambridge University Press.