MASTER OF PUBLIC POLICY
CAPSTONE PROJECT

Four Easy Ways to Reduce Canada's GHG Emissions

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Capstone Approval Page

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Table of Contents

Contents

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Executive Summary

In 2015, greenhouse gas (GHG) emissions were 722 Mt CO_2e (million tonnes CO_2 equivalent) in Canada.[1] Canada's GHG emissions goals from the Paris Agreement include reducing emissions to 523 Mt CO_2e/year by 2030 and 149 Mt CO_2e/year by 2050.[2] This paper considers four areas of potential emissions reductions, based on known technology and methods that are currently in use globally. Essentially, what can we do easily? Road transportation, sour gas plants, residential buildings, and commercial and institutional buildings are studied to determine recommendations for GHG emissions reductions. A series of quantitative metrics are laid out to test key aspects of each type of emissions reduction considered, including the economic, environmental and social feasibility in Canada, offering comparative analysis and recommendations.

Based on this analysis, with known technology in the four areas noted above, an estimated reduction of 68 Mt CO_2e/year or a 9% reduction relative to the 2015 baseline can be achieved. Of the areas considered, the most significant potential GHG reductions are in

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[1] Canada, Environment and Climate Change Canada, "Greenhouse Gas Emissions," last modified April 13, 2017, accessed June 8, 2017 from https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=En&n=FBF8455E-1

[2] Canada, Environment and Climate Change Canada, "Canadian Environmental Sustainability Indicators: Progress Towards Canada's Greenhouse Gas Emissions Reduction Target," (Gatineau, 2017), https://www.ec.gc.ca/indicateurs-indicators/CCED3397-174A-4F0E-8258-91DCFE295B34/ProgressTowardsCanadaGHGEmissionsTarget_EN.pdf

passenger and freight vehicles. The retrofitting of existing sour gas plants offers a concentrated CO_2 stream and therefore an efficient location in which to capture CO_2 with known technology. However, the total volume is relatively small and the costs are concentrated on a small stakeholder group. Strong economic incentives may be required in order to proceed with this measure. In addition to GHG emissions reductions, the vehicle and residential retrofits considered here have a modest operating cost savings incentive for consumers due to the associated reduction in energy usage.

The proposed emissions abatement projects outlined here can potentially help Canada reduce emissions by 9%, not huge but a start toward Canada's Paris Agreement goals. However, achievement of these reductions will take time. Policy choices are key to accelerating timing and level of uptake of these abatement methods. In addition, policies must consider Canadian preferences and performance over the last twenty-five years. Lower GHG emissions measures have been in the marketplace for years, but consumer preferences do not always follow even when there are economic incentives.

This paper also explores the quandary of why Canadians demonstrate two behaviours: they support carbon reduction initiatives in the forms of carbon tax and participation in the Paris Agreement, while at the same time steadfastly owning larger vehicles and living in larger homes. Evidence suggests Canadians embrace current policies and financial incentives to lower their emissions, but in general do not search out how they can reduce emissions further. In fact, their personal preferences align with economic success and growth, rather than policy ideals.

1.0 Introduction

The existence of significant human influence on the climate system through recent anthropogenic emissions of greenhouse gases in the last hundred years is clear.[3] The Intergovernmental Panel on Climate Change (IPCC) states anthropogenic greenhouse gas (GHG) emissions, together with other drivers, are extremely likely to be the dominant cause of the observed warming since the mid-20th century.[4]

In 2010, the world had annual anthropogenic GHG emissions of 49 $GtCO_2$.[5] Evidence shows future global mean surface warming into the 21st century is largely determined by cumulative emissions of CO_2.[6] The goal of CO_2 emissions reduction therefore has a temporal aspect as well: if emissions are reduced earlier, cumulative CO_2 will be lower and therefore the effects of a temperature change will be less. About 2,000 $GtCO_2$ has already been emitted between 1750 and 2010.[7] The IPCC estimates if total CO_2 emissions from all anthropogenic sources are limited to about 2,900 $GtCO_2$, then human-induced warming will be limited to less than 2 ^{o}C relative to the period 1861 to 1880, with a probability greater than 66%.[8]

The IPCC predicts continued emission of GHGs will cause further significant changes to our global climate systems, resulting in large, irreversible impacts for people and ecosystems. The proposal of reducing GHG emissions with sustained reductions in output, plus sequestration of current GHG in the atmosphere, can limit climate change risks. Anthropogenic GHG emissions are driven mainly by population, economic activity, lifestyle, energy use, land use

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[3] Rajendra Pachauri and Leo Meyer, ed., “Climate Change 2014 Synthesis Report,” Intergovernmental Panel on Climate Change, (Geneva, 2014). http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

[4] Ibid.

[5] Ottmar Edenhofer et al, ed., “Climate Change 2014: Mitigation of Climate Change – Working Group III,” Intergovernmental Panel on Climate Change, (New York, 2014). http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf

[6] Ibid.

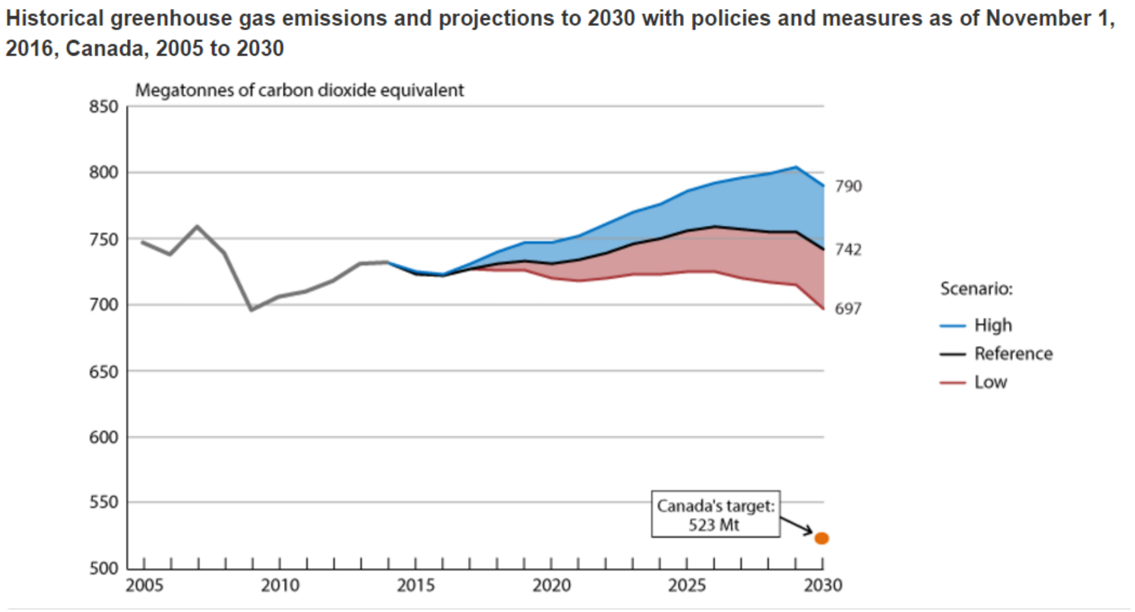
[7] Ibid. p. 45.

[8] Ibid. p. 10.

methods, technology, and climate policy. Effective management of GHG emissions and climate change will include adaptation and mitigation measures.

Canada's GHG emissions totaled 722 Mt CO_2e in 2015.[9] Canada's GHG reduction goals are based those developed by the IPCC, most recently agreed to at the Paris 2015 conference. Signatories of the Paris Agreement committed to hold the increase in the global average temperature to between 1.5 and 2.0 °C above pre-industrial levels.[10] Canada previously set a target of reducing its total GHG emissions level by 17% below 1990 levels by 2020. In Paris, this was replaced by the goal of reducing emissions by 30% below 2005 levels by 2030, or 523 MtCO_2e/year.[11] The goal is illustrated in Figure 1.[12]

Figure 1: Historical Greenhouse Gas Emissions and Projections - Canada



The Reference Case refers to the Environment and Climate Change Canada base Reference case presenting the future impacts of policies and measures taken by federal, provincial and territorial governments as of November 1, 2016, and aligned with Canada's historical emissions from 1990 to 2014. The High and Low Scenarios are Environment and Climate Change Canada cases addressing the uncertainty in key drivers, future developments in technologies, demographics and resources. Two key factors are varied – future economic growth projections, and oil and natural gas prices and corresponding production as per the National Energy Board's high and low forecast scenarios, affective November 1, 2016.

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[9] Canada, Environment and Climate Change Canada, "Greenhouse Gas Emissions," last modified April 13, 2017, accessed June 8, 2017 from https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=En&n=FBF8455E-1

[10] United Nations, "Paris Agreement," Paris, (2015). http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

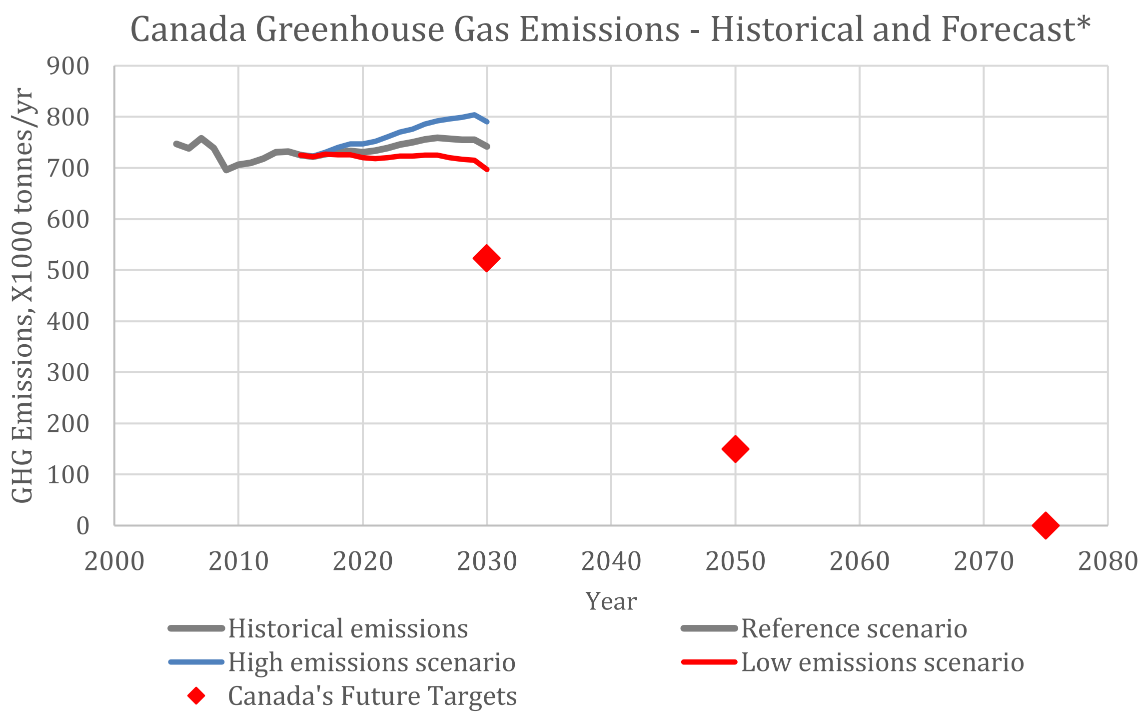
[11] Canada, "Canada's INDC Submission to the UNFCCC," (2015). http://www4.unfccc.int/ndcregistry/PublishedDocuments/Canada%20First/INDC%20-%20Canada%20-%20English.pdf

[12] Canada, Environment and Climate Change Canada, "Canadian Environmental Sustainability Indicators."

Source: Canada, Environment and Climate Change Canada, “Canadian Environmental Sustainability Indicators: Progress Towards Canada’s Greenhouse Gas Emissions Reduction Target,” (Gatineau, 2017), https://www.ec.gc.ca/indicateurs-indicators/CCED3397-174A-4F0E-8258-91DCFE295B34/ProgressTowardsCanadaGHGEmissionsTarget_EN.pdf

Canada has also committed to reach a level of 80% reduction from 2005 levels by 2050. In addition, the long-term goal is zero emissions in 2075 from the Paris Agreement and IPCC. Imposing these numbers on Figure 1, the result is shown in **Error! Reference source not found.**:[13]

Figure 2: Canada Greenhouse Gas Emissions Historical and Future Targets



* Source =(2017). “Canadian Environmental Sustainability Indicators: Progress Towards Canada’s Greenhouse Gas Emissions Reduction Target.” Gatineau. Government of Canada. Retrieved from https://www.ec.gc.ca/indicateurs-indicators/CCED3397-174A-4F0E-8258-91DCFE295B34/ProgressTowardsCanadaGHGEmissionsTarget_EN.pdf

Note: The Reference Case refers to the Environment and Climate Change Canada base Reference case presenting the future impacts of policies and measures taken by federal, provincial and territorial governments as of November 1, 2016, and aligned with Canada’s historical emissions from 1990 to 2014. The High and Low Scenarios are Environment and Climate Change Canada cases addressing the uncertainty in key drivers, future developments in technologies, demographics and resources. Two key factors are varied – future economic growth projections, and oil and natural gas prices and corresponding production as per the National Energy Board’s high and low forecast scenarios, affective November 1, 2016.

Source: Canada, Environment and Climate Change Canada, “Canadian Environmental Sustainability Indicators: Progress Towards Canada’s Greenhouse Gas Emissions Reduction Target,” (Gatineau, 2017). Retrieved from https://www.ec.gc.ca/indicateurs-indicators/CCED3397-174A-4F0E-8258-91DCFE295B34/ProgressTowardsCanadaGHGEmissionsTarget_EN.pdf

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[13] Canada, Environment and Climate Change Canada, “Canadian Environmental Sustainability Indicators.”

This paper considers the significant and steep reduction in GHG emissions forecast above, and evaluates what Canada can do to reduce GHG emissions immediately. Much of current policy focuses on new technology and innovation as a potential solution to move Canada toward its goals.[14] However, this approach has inherent unknowns in timing, cost, and effectiveness. This report proposes methods of GHG reduction that can be implemented immediately, utilizing known technology currently available and in use in significant amounts globally. Areas considered are:

1. Road transportation: passenger and freight.
2. Fossil fuel extraction: gas plant carbon capture and storage (CCS) retrofit.
3. Residential retrofit: lighting, appliances, heating, hot water heating.
4. Commercial and institutional retrofit: lighting, heating.

Emissions from transportation represent 24% of Canada's total GHG emissions in 2015.[15] This area is chosen as it represents a significant percentage of GHG emissions for Canada. A number of sour gas plants in Canada exist with successful CCS installations: CO_2, in conjunction with H_2S (hydrogen sulfide) and other impurities, is sequestered and reinjected into a storage reservoir underground. This area is considered as it represents an economic sector where the applicable technology is proven and successfully in use. Emissions from buildings represent 12% of Canada's total GHG emissions including residential and commercial/institutional,[16] therefore

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[14] Canada, "Budget 2017 – Budget Plan," (Ottawa, 2017). http://www.budget.gc.ca/2017/docs/plan/toc-tdm-en.html; "Innovation, Science and Economic Development Canada – Departmental Plan," Government of Canada, Ottawa, (2017). www.ic.gc.ca/eic/site/017.nsf/eng/h_07599.html.

[15] Canada, Environment and Climate Change Canada, "Greenhouse Gas Emissions by Canadian Economic Sector," last modified April 13, 2017, accessed July 7, 2017. https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=F60DB708-1

[16] Ibid.

this area is chosen as it is a significant segment of Canada’s emissions also. Combined, the four areas represent approximately 38% of Canada’s emissions.

In the four sectors considered, this paper attempts to quantify what Canada can easily do to significantly reduce GHG emissions, at what cost, and within what timeframe. For each sector, assumptions are first laid out, including evaluation of the baseline business as usual (BAU) emissions levels and the proposed abatement methods for reduction in GHG emissions. Next, the analysis for each sector contains an estimate of costs related to the proposed abatement measures and a discussion of proposed timeframe behind these measures. Finally for each sector, policy recommendations are made, discussing the strengths and weaknesses of each, the challenges of implementation, and whether the policies are complementary to carbon pricing. The paper closes with a discussion comparing each abatement measure and its cost relative to the social cost of carbon. A commentary on the overall feasibility and desirability of the proposed measures completes the discussion.

Each area will be discussed individually, including an analysis of the following metrics:

- Business As Usual (BAU) emissions level, $MtCO_2e$/year
- Lower GHG emissions case, $MtCO_2e$/year
- Capital intensity of abatement measure (incremental capital invested versus tonnes abatement for life of project) - \$/tonne CO_2e
- Abatement cost (incremental operating cost compared to BAU case, net present value discounted over life of project) - \$/tonne CO_2e
- Materiality – maximum benefit of abatement measure for Canada – Mt CO_2eq/year reduction
- Social cost of carbon and social savings - \$/tonne CO_2e
- Political and social feasibility

1.1 General Assumptions

Canada's 2015 GHG emissions levels are used as a BAU baseline emissions level. Key changes in equipment and/or practices are proposed using known technology with lower GHG emissions potential. In this manner, a lower GHG emissions case is developed for each mitigation measure.

The potential timeframe of implementation will be discussed specifically for each mitigation measure, and the associated costs will also be estimated. The value of these mitigation measures is considered over a twenty-year period, compared to a BAU case of the same lifespan. Costs in both cases are inflated in the future with a 1.7% annual inflation rate, which represents the average inflation rate from Statistics Canada from 2010 to 2016.[17]

A discount rate of eight percent is assumed for all net present value analysis. This assumption is based on the Treasury Board of Canada's guidelines on cost-benefit analysis for regulatory proposals. The future cash flow is discounted based on the opportunity cost of capital, as estimated by the Treasury Board of Canada.[18]

A discounted net present value of the incremental capital and operating costs is calculated for each abatement measure. This number is then annualized over the life of the project to determine annual costs or savings. This annualized amount represents the fixed annual stream of income that would be paid by a fixed-interest annuity with the same net present value as the project.[19] The net present value is also divided by the amount of CO_2e abatement for the life of the project to calculate the abatement cost on a per tonne basis.

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[17] Canada, Statistics Canada, "Consumer Price Index, Historical Summary," Ottawa, last modified January 20, 2017, accessed August 28, 2017. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm

[18] Canada, Treasury Board of Canada Secretariat, "Cost-Benefit Analysis Guide," (Ottawa, 2007), p. 37. https://www.tbs-sct.gc.ca/rtrap-parfa/analys/analys-eng.pdf

[19] European Commission, "Better Regulation Toolbox," (2015). http://ec.europa.eu/smart-regulation/guidelines/docs/br_toolbox_

In addition to the assumption of twenty-year lifespans, energy demand in passenger vehicles, residential use, commercial and institutional buildings, and gas processing plants is assumed to be flat rather than increasing or decreasing. All net present values, benefits and costs are reported in 2017 Canadian dollars, using Statistics Canada's inflation rates for correction as required. For the case of freight vehicles, the BAU case and the lower emissions case assumes an annual rate of increase in mileage of 3.7%.

In the cases of households, data from 1990 through 2014 indicates Canadians are increasing their energy use:[20] square footage of the average Canadian house is increasing, in addition to general population growth. However, confounding factors such as new, more energy-efficient technology, a paradigm shift to other technologies or practices, or economic downturns, work against growth in Canadian energy use and have resulted in relatively flat GHG emissions from households between 1990 and 2014.[21]

Considering commercial and institutional building energy use in Canada, from 1990 to 2000 total energy increased, and remained constant from 2000 to 2014. Corresponding GHG emissions increased to 2000 and were flat to declining from 2000 to 2014, indicating a general correlation between the two.[22] From 2000 to 2014, energy used per square metre of space declined, indicating confounding factors of increasing space but improved efficiency once again work against each other to result in a flat go-forward base case for energy use and GHG emissions.[23]

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[20] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables," retrieved 2017-07-07. http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

[21] Canada, Environment and Climate Change Canada, "Greenhouse Gas Emissions by Canadian Economic Sector."

[22] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

[23] Ibid.

Similarly, Canadian passenger vehicle use has increased over time due to population increases, however changes in per capita mileage and fuel efficiencies of the fleet have resulted in unchanging GHG emissions from 2002 to 2014.[24]

Natural gas processing volumes in Canada have varied with time, however total natural gas sales have been relatively flat from 2000 to 2017.[25]

Based upon this data, this study assumes constant energy use as a base case for passenger vehicles, residential energy use, commercial and institutional building energy use, and natural gas processing volumes.

In the case of freight transportation, the BAU scenario is different: historical data shows a steady increase in mileage of 3.6% per year from 2008 to 2014.[26] For comparison, GDP growth for the same time period averaged 1.6% annual growth.[27] During this same period, fleet fuel efficiency improved by 1.3% per year, but GHG emissions increased 2.3% per year.[28] The confounding effects were not enough to flatten emissions growth. In this case, energy use is assumed to grow at 2.3% per year for both the BAU case and the lower GHG emissions case.

1.2 Social Cost of Carbon Estimates

The social cost of carbon (SCC) is defined by a large literature, with a lack of consensus due to uncertainty in costs, future impacts, and potential offsetting benefits of anthropogenic climate change. In addition, the SCC will vary depending on the region or reference group

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[24] Ibid.

[25] Canada, National Energy Board, “Marketable Natural Gas Production in Canada,” last modified August 14, 2017, accessed August 15, 2017. https://www.neb-one.gc.ca/nrg/sttstc/ntrlgs/stt/mrktblntrlgsprdctn-eng.html

[26] Canada, Natural Resources Canada, “Energy Use Data Handbook Tables.”

[27] Ibid.

[28] Ibid.

considered. Lower values assume that climate change will have small to negligible effects, while larger estimates imply the impacts of climate change are catastrophic.[29]

The calculation of the SCC is performed typically using an integrated assessment model, or IAM, which considers numerous parameters and assumes a social discount rate and a level of risk aversion.[30] Anthoff and Tol demonstrate a large variation in SCC for various global regions, all other parameters held constant.[31] In this paper, we use the SCC estimates from Environment and Climate Change Canada issued in March 2016. Environment and Climate Change Canada calculates the aggregated, central tendency for the SCC at $40.70/tonne (2012 $Cdn) for 2016, and the corresponding 95th percentile figure at $167/tonne (2012 $Cdn).[32] The central tendency value grows at 2.0% per year while the 95th percentile figure increases at 2.25% per year.[33] Updated for growth and inflation, we use the following SCC values when comparing to calculated abatement costs herein, expressed in 2017 Canadian dollars:

- Central SCC Estimate = $44.23 per tonne CO_2
- 95th Percentile SCC Estimate = $181.96 per tonne CO_2

Abatement costs calculated for various measures are compared to the SCC figures above. If an abatement cost is higher than the SCC, the cost outweighs the benefit. The above figures are also compared to the carbon tax backstop announced by the federal government.

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[29] Ker Than, “Estimated social cost of climate change not accurate, Stanford scientists say,” *Stanford News*, January 12, 2015, http://news.stanford.edu/2015/01/12/emissions-social-costs-011215/

[30] D. Anthoff and R. Tol, “The uncertainty about the social cost of carbon: A decomposition analysis using FUND,” *Climatic Change*, Vol. 117, Issue 3, (2013), pp. 515-530. http://link.springer.com/10.1007/s10584-013-0706-7; J. van den Bergh and W. Botzen “Monetary valuation of the social cost of CO2 emissions: A critical survey.” *Ecological Economics*, Vol. 114, (2015), pp. 33-46. http://linkinghub.elsevier.com/retrieve/pii/S0921800915001007

[31] Ibid.

[32] Canada, Environment and Climate Change Canada, “Technical Update to Environment and Climate Change Canada’s Social Cost of Greenhouse Gas Estimates,” (Gatineau, 2016). collection_2016/eccc/En14-202-2016-eng.pdf

[33] Ibid.

2.0 Passenger and Freight Road Transportation: Canada's Passion

2.1 Passenger Transportation

2.1.1 Assumptions

Transportation accounted for 24% of Canada's GHG emissions in 2015.[34] Eighty-five per cent of this figure, or 146 Mt CO_2e, is from road transportation.[35] National Energy Use Database data shows for passenger vehicles, GHG emissions were 69.1 Mt CO_2e[36] (2014 data, as 2015 NEUD data is not yet available).

In 2014, Canada averaged 219 grams CO_2e/km emissions for all passenger vehicles. [37] Also in that year, Canadian drivers covered 314,753 million vehicle-kilometres in passenger travel, and passenger vehicle fuel efficiency averaged 8.8 litres per 100 kilometres travelled.[38] GHG emissions have been flat for passenger vehicles from 2002 to 2014; therefore the BAU case has constant vehicle-kilometres and fuel efficiency to 2017 and through the twenty-year life cycle considered.[39]

Fuel economy has a wide range in OECD and non-OECD countries. Canada has one of the poorest average fuel economies, while Japan has one of the best.[40] Japan achieved 119 g CO_2e/km in its new 2014 vehicles in the EU market, and 102 g CO_2e/km in its 2014 domestic new vehicles.[41] In 2015, Japan's stock of passenger vehicles was 0.6% electric vehicles (battery

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[34] Canada, Environment and Climate Change Canada, "Greenhouse Gas Emissions by Canadian Economic Sector."

[35] Ibid.

[36] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

[37] Ibid.

[38] Ibid.

[39] Ibid.

[40] Lew Fulton and Sheila Watson, ed., "Fuel Economy State of the World 2014," *Global Fuel Economy Initiative*, (2015). https://www.fiafoundation.org/media/44209/gfei-annual-report-2014.pdf; Francois Cuenot and Lew Fulton, "International comparison of light-duty vehicle fuel economy and related characteristics," OECD, IEA, (Paris, 2011). https://www.globalfueleconomy.org/media/44069/wp5-iea-fuel-economy-report.pdf

[41] "2016 Report on Environmental Protection Efforts - Promoting Sustainability in Road Transport in Japan," Japan Automobile Manufacturers Association, Inc., (2016), p.10. http://www.jama-english.jp/publications/env_prot_report_2016.pdf

electric and plug-in hybrid combined) while Canada's stock of the same was 0.4%.[42] The emissions levels seen in Japanese vehicles are primarily due to the lower average weight of passenger vehicles with internal combustion engines, rather than a difference in power source. Japanese fuel efficiency regulations set 2015 average new vehicle fleet emissions levels at 135 g CO_2e/km, while the 2020 emissions level is 113 g CO_2e/km, as their stock continues to become more fuel efficient over time.[43]

The lower emissions case, "High Fuel Efficiency Case," assumes all passenger vehicles in Canada are replaced with vehicles having a GHG emissions level of 119 g CO2e/km using immediately available automobile technology, compatible with Canada's current fuel delivery infrastructure. Japan currently produces vehicles with a range of emissions from 102 to 119 g CO_2e/km, and we assume Canada will change over its fleet and lower subsequent GHG emissions. The price of a vehicle in the BAU case is assumed equal to the price of a low GHG emissions vehicle. This results in zero incremental capital cost between the BAU Case and the High Fuel Efficiency Case. Fuel costs are estimated based upon the April 2017 average gasoline cost in Canada, $1.16/litre,[44] and inflated at 1.7% per year. Future values are discounted at eight percent.

A related issue is the assumed timeframe in which the GHG reductions will be achieved. If we assume these reductions are achieved immediately, there is an incremental capital cost to replace the current fleet before it has lived out its life. Alternatively, the fleet may be changed out over time as vehicles are retired, resulting in the full cuts being achieved after a number of

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[42] "Global EV Outlook 2016 Electric Vehicles Initiative," International Energy Agency, (Paris, 2016). https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2016.pdf

[43] Atsuto Kajiwara, "Overview of FY2020 Fuel Efficiency Standards for Passenger Vehicles," Ministry of Land, Infrastructure, Transport, and Tourism, (2012). https://www.unece.org/fileadmin/DAM/trans/doc/2012/wp29grpe/GRPE-63-07e.pdf

[44] Canada, Statistics Canada, "Average Retail Prices for Gasoline and Fuel Oil, By Urban Centre," date modified August 18, 2017, http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=3260009

years. We assume consumers replace their vehicles as they reach end of useful life, all over a twenty year period. In the BAU case the replacement vehicle is any choice, while in the High Fuel Efficiency Case it is a lower emissions vehicle. To test the reasonableness of this assumption, consider the average age of vehicles in Canada and the estimated time required to replace the entire fleet. The distribution of the vintage of light vehicles in Canada in 2009 is as follows (no later data available):[45]

Table 1: Age of Canadian Vehicles, Passenger Vehicles

	Percentage	**Number**
Less than 3 years	18.7	3,694,362
3 – 5 years	22.2	4,385,820
6 – 9 years	28.0	5,531,665
10 – 13 years	16.7	3,299,243
More than 13 years	14.4	2,844,856
TOTAL	**100.0**	**19,755,945**

Source: Natural Resources Canada, "Canadian Vehicle Survey – 2009 Summary Report," (2011), Government of Canada, Ottawa. http://publications.gc.ca/collections/collection_2012/mcan-nrcan/M141-18-2009-eng.pdf

Based upon the fleet age noted above for light passenger vehicles in Canada, a twenty-year period is reasonable to change substantially all vehicles to the lower emissions levels as they get replaced. Assuming a twenty year period and 19.76 million vehicles, 988 thousand vehicles are changed out per year.

2.1.2 Analysis

The abatement method considered here is the changeover of the fleet of passenger vehicles to higher fuel efficiency vehicles. Table 2 presents a summary of emissions reduction figures and corresponding estimated abatement costs.

Table 2: Estimated Abatement Costs, Passenger Vehicles

	BAU	**High Fuel Efficiency Case**
Project Life	20	20
I. Capital Costs (compared to BAU case)		Same price as in BAU case

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[45] Canada, Natural Resources Canada, "Canadian Vehicle Survey – 2009 Summary Report," (Ottawa, 2011), p.28. https://oee.nrcan.gc.ca/publications/statistics/cvs/2009/index.cfm

Total Capital Costs Above BAU	$ -	$ -
II. Operating Costs per year		
Vehicle-km - millions, 2017 estimate	314,753	314,753
Average 2017 Fuel Efficiency, l/100 km[1]	8.8	4.8
Estimated emissions, gm CO_2eq/km	219	119
Annual Fuel Costs, Net Present Value[2] (millions $Cdn)	$ 19,745	$ 10,729
Annual Fuel Cost Savings above BAU-Incremental Net Present Value (millions $Cdn)		-$ 9,016
CO_2eq Mt/yr	69	37
CO_2eq Reduction, Mt/yr		31
Abatement Costs, Capital - $/t CO_2		**$0**
Abatement Costs, Opex - $/t CO_2		**-$286**

1. Average April 2017 gasoline price = $1.16/litre, source = Statistics Canada, CANSIM, table 326-0009 and Catalogue no. 62-001-X
2. Inflation rate 1.7%, discount rate = 8%.

The abatement cost is estimated at -$286 per tonne CO_2e, representing significant potential savings in fuel costs for Canadians through replacement of all passenger vehicles. These savings will be implemented gradually over a twenty-year period as the national fleet of passenger vehicles is replaced. At the same time, the SCC increases with time, indicating these GHG emissions reductions will become increasingly valuable in the future.

2.1.3 Policy Recommendations

A policy unique to Canada's demographics and geography is required to achieve the targeted 31 Mt CO_2e/year reduction. With Canada's extensive travel distances combined with active, sprawling urban centres, Canadians have a unique dependence on road travel. In many OECD countries, overall demand for passenger travel has historically grown roughly proportionally with per capita GDP and population growth.[46] A public transportation sector can become more efficient, but Lipscy and Schipper argue the reasons have less to do with

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[46] "ITF Round Tables: Long-run Trends in Car Use," OECD International Transport Forum, (2013). http://www.oecd-ilibrary.org.ezproxy.lib.ucalgary.ca/docserver/download/7413041e.pdf?expires=1499714995&id=id&accname=ocid57005644&checksum=BA4FD77F108AFFC43BF7147E21A20212

government policies, and more to do with demographics, geography and rising energy costs.[47] Canada's geography is extreme compared to most OECD countries, therefore a policy that suits our unique qualities is considered here: a significant increase in the mandatory fuel efficiency regulations is recommended, implemented over a number of years, and based upon "best-in-class" fuel efficiencies seen globally rather than just North American markets. With the geography of Canada and its underlying personal transportation needs, this policy recommendation allows Canadians to continue current behaviour while significantly reducing GHG emissions.

Canadians will still have the option of driving long distances and there will always be a range of vehicle size to be used, but the range will continue to go down significantly with time. Lower GHG emissions options will be introduced and encouraged through command and control regulation and complementary education policy. Urban concentrations of Canadian drivers are targeted specifically with education because it is here behaviours can be modified and models from other OECD countries can be implemented.

This policy is potentially complementary to a carbon tax on fuel. Studies show while both a fuel tax and fuel efficiency standards may have positive effects on fuel reduction and therefore GHG emissions reduction targets, use of a carbon tax alone may require a large increase in fuel prices to realize the same fuel reductions as imposing regulated standards.[48] In addition, fuel standards may be seen as politically more palatable than extreme fuel tax imposition, as it can be

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[47] P. Lipscy and L. Schipper, "Energy efficiency in the Japanese transport sector," *Energy Policy*, Vo. 56, pp. 248-258, (2013). Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0301421512010981

[48] S. Clerides and T. Zachariadis, "The effect of standards and fuel prices on automobile fuel economy: An international analysis," *Energy Economics*, Vol. 30, Issue 5, pp. 2657-2672, (2008). http://linkinghub.elsevier.com/retrieve/pii/S0140988308000832; P. Goldberg, "The Effects of the Corporate Average Fuel Efficiency Standards in the U.S.," *The Journal of Industrial Economics*, Vol. 46, (1998), http://www.jstor.org.ezproxy.lib.ucalgary.ca/stable/117529

represented as a consumer choice between vehicles rather than impacting a consumer need of fuel.

From 1990 to 2014, the average annual GHG emissions per passenger vehicle decreased by 28%.[49] Fuel efficiency standards are proven to be an effective and economically efficient policy instrument to reduce GHG emissions in the road transport sector.[50]

In 2010, the Company Average Fuel Consumption (CAFC) targets for passenger cars and light trucks in Canada became mandatory through the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations,[51] implemented under the *Canadian Environmental Protection Act* (CEPA).[52] Targets follow those in the U.S. and have a similar penalty payable by automobile manufacturers should fleet targets not be achieved.[53] Canada has already improved its average passenger fleet fuel economy and therefore reduced its GHG emissions substantially since these regulations were put in place. Canada's average emissions from passenger vehicles fell from 259 g CO_2e/km to 219 g CO_2e/km between 1990 and 2014, a 15% reduction. Canada's Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations impose maximum GHG fuel emissions levels separately for both passenger cars and passenger light trucks on the Canadian market up to 2025, with a lower and upper range for each category:

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[49] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

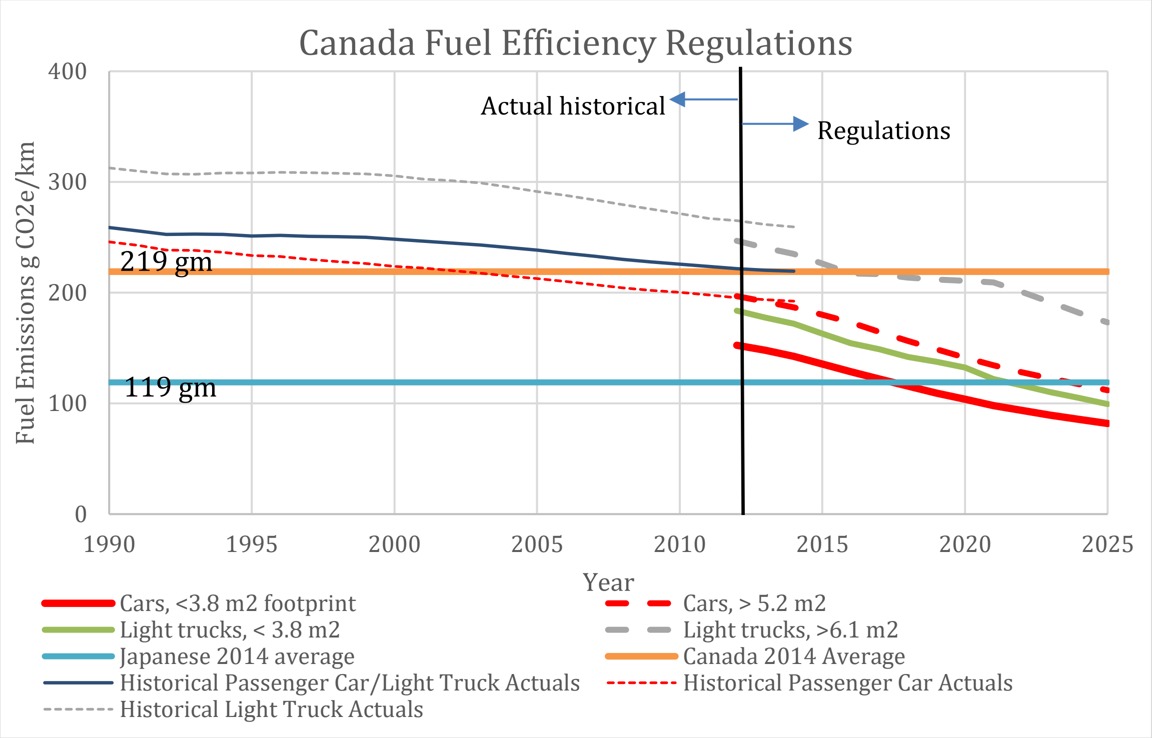
[50] Felix Creutzig, Emily McGlynn, Jan Minx, and Ottmar Edenhofer, "Climate policies for road transport revisited (I): Evaluation of the current framework," *Energy Policy*, (2011), Vol. 39, Issue 5, pp. 2396-2406. http://linkinghub.elsevier.com/retrieve/pii/S0301421511000760

[51] *Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations*, SOR/2010-201, <http://canlii.ca/t/52hms> retrieved on 2017-07-07

[52] *Canadian Environmental Protection Act*, 1999, SC 1999, c 33, <http://canlii.ca/t/52z4m>

[53] Shawn McCarthy, "Canada to copy Obama's fuel efficiency rules," *The Globe and Mail*, August 30, 2012. https://www.theglobeandmail.com/report-on-business/industry-news/energy-and-resources/canada-to-copy-obamas-fuel-efficiency-rules/article4508608/

Figure 3: CAFC GHG Fuel Emissions Regulations for Passenger Vehicles - Canada



Note: the CAFC regulations denote a lower and upper bound for passenger cars and light trucks, with the maximum allowable emissions level depending on vehicle "footprint" in square metres, calculated by the length and width of the wheel base.
Sources: Data from Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations, SOR/2010-201, <http://canlii.ca/t/52hms> retrieved on 2017-08-15; and Natural Resources Canada - Energy Use Data Handbook Tables - http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

Figure 3 illustrates the progress to date, but also shows Canadian consumer preferences. The "Historical Passenger Car/Light Truck Actuals" in Figure 3 move up away from the "Historical Passenger Car Actuals", and closer to the "Historical Light Truck Actuals" because sales of cars fell in that time period while light trucks, including sport utility vehicles sales, rose, resulting in a slower decline in GHG emissions for the overall fleet than seen in passenger cars alone. This confounding effect needs to be dealt with potentially through a complementary policy or regulation. If higher emissions vehicles are preferred by consumers within the range of what is available, two potential options could improve smaller vehicle uptake: curb weight limits on the largest categories of vehicles, reducing from 2017 through 2025 in conjunction with emissions limits, and some increase in the penalty paid by manufacturers when not meeting these targets, similar to that seen in the U.S. in 2015.[54]

The historical fuel efficiency figures are actual efficiencies from Canada's current fleet of passenger cars owned by consumers, while the regulatory data shown in the above graph denotes the manufacturers' fleet of vehicles for sale. It will take some years for the manufacturers' emissions levels to fully integrate into the fleet on the road.

Pros:

Clerides and Zachariadis show the use of fuel efficiency regulations are important for improvements in fleet greenhouse gas emissions.[55] They conclude if the 130 g CO_2e/km target had to be abandoned in Europe, a 50% increase in fuel taxes, whether from a carbon tax or other, would be necessary to induce similar fuel and GHG emissions savings.[56] In this example, gasoline price was $1.06 Cdn per litre (2017 dollars) with an original tax of $0.31 Cdn (2017). To see the same reduction in fuel usage, Clerides and Zachariadis estimate a tax of $0.50 Cdn (2017) per litre would be required. For comparison, the average gasoline price in Canada in 2015 was $1.06 per litre (2017 dollars), and of that, the tax portion averaged $0.33 per litre (2017).[57] Similarly, Goldberg estimates a doubling of gasoline prices would be required to achieve equivalent fuel consumption reductions to the CAFE regulations results in the U.S. in 1989.[58] Clerides and Zachariadis also show independent improved fuel efficiency development by automobile manufacturers would not continue to increase without regulations. They find technology would continue to be developed but would be exploited in ways that do not yield fuel

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[54] Ryan Beene, "U.S. to revisit penalties for fuel-economy shortfalls," *Automotive News*, July 7, 2017. http://canada.autonews.com/article/20170707/OEM/307079896/u.s.-to-revisit-penalties-for-fuel-economy-shortfalls#

[55] S. Clerides and T. Zachariadis, "The effect of standards and fuel prices."

[56] Ibid.

[57] PetroCanada, "Gasoline Taxes/Levies Across Canada," accessed August 29, 2017. http://retail.petro-canada.ca/en/fuelsavings/gas-taxes-canada.aspx

[58] P. Goldberg, "The Effects of the Corporate Average Fuel."

savings.[59] Sperling and Yeh note fuel efficiency regulations are a less efficient approach than carbon tax theoretically, but also find in practice high gasoline prices in Europe resulted in little change in choice of fuels.[60] Atabani et al show with a reduction in weight of 100 kilograms of the average European car, fuel consumption is reduced by 0.2 litres per 100 kilometres, and GHG emissions are reduced by a corresponding 2.3 to 4.2% considering the 2014 average GHG emissions level for Canadian and Japanese passenger vehicles.[61] One of the major methods of continued GHG reduction is therefore reducing vehicle weight.

Cons:

Command-and-control regulations such as mandatory fuel efficiency limits do not provide an incentive to go beyond the minimum standard.[62] Ford, GM, and Chrysler average fuel efficiencies have followed CAFÉ standards closely, with some years being slightly above and others slightly below.[63]

As fuel efficiencies continue to be improved, the welfare impact on consumers must be considered.[64] Studies show that while a carbon tax on fuel is regressive, a vehicle fuel efficiency standard is even more regressive.[65] Poorer households choose the low-fixed-cost, high-variable cost models, they consume more used vehicles rather than new, and they average lower

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[59] S. Clerides and T. Zachariadis, “The effect of standards and fuel prices.”

[60] S.Yeh and D.Sperling, “Low carbon fuel standards: Implementation scenarios and challenges,” *Energy Policy*, (2010), Vo. 38, Issue 11, pp.6955-6965. Retrieved from http://www.sciencedirect.com.ezproxy.lib.ucalgary.ca/science/article/pii/S0301421510005410

[61] A. Atabani, I. Badruddin, S. Mekhilef, I. Anjum and A.S. Silitonga, “A review on global fuel economy standards, labels and technologies in the transportation sector,” *Renewable and Sustainable Energy Reviews*, Vol. 15, Issue 9, (2011), pp.4586-4610. http://linkinghub.elsevier.com/retrieve/pii/S1364032111003376

[62] Georgina Santos, Hannah Behrendt, Laura Maconi, Tara Shirvani, Alexander Teytelboym, “Part I: Externalities and economic policies in road transport,” *Research in Transportation Economics*, Vol. 28, Issue 1, (2010), pp. 2-45. http://linkinghub.elsevier.com/retrieve/pii/S0739885909000584

[63] Mark Jacobsen, “Evaluating U.S. Fuel Economy Standards in a Model with Producer and Household Heterogeneity,” University of California at San Diego, (2012). http://econweb.ucsd.edu/~m3jacobs/Jacobsen_CAFE.pdf

[64] S. Clerides and T. Zachariadis, “The effect of standards and fuel prices.”

[65] Mark Jacobsen, “Evaluating U.S. Fuel Economy Standards”; Arik Levinson, “Energy Efficiency Standards are More Regressive than Energy Taxes: Theory and Evidence,” Georgetown University and National Bureau of Economic Research, (2016). http://faculty.georgetown.edu/aml6/pdfs&zips/RegressiveMandates.pdf

kilometres per year also.[66] These factors contribute to regressivity of both energy taxes and the cost of fuel efficiency programs. A major difference between the two is a fuel tax imposes immediate costs to the consumer, while fuel efficiency regulations imposed over time may be more palatable due to their gradual nature as the fleet is replaced.

The timeframe with which the regulations are implemented must be similar to average vehicle lifespan and costs of smaller, higher fuel efficiency vehicles must be controlled in order to minimize welfare impacts. There is also a documented negative safety impact with decreasing vehicle size. Shi and Nushotlz show the fatality risk follows a general linear trend with vehicle weight, increasing by about 1.8% per 100 kilograms decrease in vehicle weight.[67] As this policy is implemented, the range of vehicle weights should be managed to reduce any significant adverse impacts.

Political and Social Feasibility

CAFÉ regulations are rapidly increasing required fleet fuel efficiencies from 2017 to 2025. In conjunction with this, in 2015, significantly higher penalties were imposed in the U.S. should a manufacturer not meet the annual fleet specifications. Automobile manufacturers see this as a potential challenge when combined with the rapidly falling targets, and have lobbied the U.S. government to reduce the penalties.[68] It is not clear in publicly available data how many manufacturers meet the targets versus choosing to pay penalties but some luxury vehicle manufacturers are said to be impacted most significantly by these changes.[69] If the main method

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[66] A. Levinson, "Energy Efficiency Standards are More Regressive."

[67] Shi Yibing, Guy Nusholtz, "Fleet Fatality Risk and its Sensitivity to Vehicle Mass Change in Frontal Vehicle-to-Vehicle Crashes, Using a Combined Empirical and Theoretical Model," *Stapp Car Crash Journal*, Volume 59, (2015), pp. 297-312. https://search-proquest-com.ezproxy.lib.ucalgary.ca/abicomplete/docview/1809575006/49A1AB1596954703PQ/36?accountid=9838

[68] Ryan Beene, "U.S. to revisit penalties for fuel-economy shortfalls," *Automotive News*, (2017-07-07). http://canada.autonews.com/article/20170707/OEM/307079896/u.s.-to-revisit-penalties-for-fuel-economy-shortfalls#

[69] Ibid.

of reducing emissions and increasing fuel efficiency is reducing vehicle weight, safety and emissions will have to be balanced in an acceptable combination for consumers. The buying habits of Canadian consumers have shown from 1990 to 2014 smaller cars are losing market share while light trucks and SUV's are increasing, indicating the general public may not be accepting of the required significant drop in vehicle size corresponding to GHG emissions reduction. Additional incentives could nudge consumers toward these vehicles in greater numbers.

2.2 Freight Transportation

2.2.1 Assumptions

In 2014 freight transportation in Canada using light, medium and heavy trucks travelled 130,163 million km.[70] In that year, GHG emissions from freight vehicles totaled 71 Mt CO_2e.[71] The average emissions level for freight vehicles in 2014 was 549 g CO_2e/km.[72] Freight comprises 29% of combined freight and passenger vehicle-kilometres in Canada, but contributes 51% of road transportation GHG emissions.[73]

We consider a simple method using existing technology with which to significantly reduce GHG emissions from freight vehicles in Canada, and we quantify this method in both achievable volume and cost. The abatement method considered here is replacement of all vehicles with natural-gas-powered trucks.

Based upon historical trends, energy use in the BAU case is assumed to increase at 2.3% per year from 2014 to 2017, reflecting an increase of vehicle-km of 3.6% per year combined with

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[70] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."
[71] Ibid.
[72] Ibid.
[73] Ibid.

a decrease in emissions per kilometre of 1.3% per year.[74] A 2.3% annual increase in forecast energy use is therefore assumed for both the BAU case and the lower emissions case; the difference between the two cases is the type of energy used. A twenty-year period is assumed as the lifecycle required to change out all vehicles. In 2014, the total number of freight vehicles in Canada was 4.8 million, with total mileage for that year of 130 billion kilometres.[75] The average emissions level for freight vehicles in 2014 was 549 g CO_2e/km. Applying the historical trends above, the 2017 freight kilometres is 139 billion kilometres.

Compressed natural gas (CNG) and liquefied natural gas (LNG) freight vehicles have a significant incremental capital cost up front compared to an equivalent size diesel truck. For heavy freight trucks, estimates of incremental cost range from $51,000 to $65,000 per truck; this paper assumes an incremental cost of $58,000 per vehicle.[76] For medium and light freight trucks, a premium of 31% is applied based upon National Petroleum Council estimates.[77] The base price for medium and light commercial trucks is assumed at $43,778, from 2017 sales data.[78] In 2014 there were 2,722,462 light freight vehicles, 1,603,035 medium freight vehicles, and 455,004 heavy freight vehicles in Canada.[79] We assume these levels remain constant through 2014 to end of the 20 year lifecycle. When calculating the net present value of capital costs, they are spread evenly throughout the twenty year life considered.

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[74] Ibid.

[75] Ibid.

[76] "Is Natural Gas Trucking's Future, or is CNG Just a Pit Stop on the Way to Electric Semi-Trucks?" *Oil & Gas 360*, (2017). https://www.oilandgas360.com/is-cng-truckings-future-or-just-a-pit-stop-on-the-way-to-electric-semi-trucks/; Stephen Edelstein, "Why Aren't Natural Gas-Powered Long-Haul Semi Trucks Selling Better?" *Green Car Reports*, (2014). http://www.greencarreports.com/news/1094087_why-arent-natural-gas-powered-long-haul-semi-trucks-selling-better; John Smith, "A Price on Carbon, but Support for Natural Gas?" *Today's Trucking*, (2016). https://m.todaystrucking.com/a-price-on-carbon-but-support-for-natural-gas; Mitch Carlson, "Natural Gas as a Transportation Fuel – Properties, Benefits, & SaskEnergy Support," BayhurstGas, a SaskEnergy Company, (2015). http://www.gowithnaturalgas.ca/wp-content/uploads/2015/01/Natural-Gas-As-Transportation-Fuel.pdf

[77] National Petroleum Council, "Natural Gas,"Advancing Technology for America's Transportation Future," (Washington, 2012). http://www.npc.org/reports/FTF-report-080112/Chapter_14-Natural_Gas.pdf

[78] Canada, Statistics Canada. "Table 079-0003 - New motor vehicle sales, Canada, provinces and territories, monthly," CANSIM. http://www5.statcan.gc.ca/cansim/a47

[79] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

Studies show on a well-to-wheels basis natural gas fuel emits 22% less GHGs than diesel and 29% less than gasoline vehicles, for a weighted average of 25% lower emissions.[80] In addition, natural gas engines are less efficient than similarly sized diesel engines, with a typical difference of about 12%.[81] The cost savings and GHG emissions reduction for fuel must therefore be reduced by 12%.

Cost savings include the reduced fuel costs through replacing the gasoline or diesel with CNG. CNG retail price averaged $0.855/litre-gasoline equivalent (LGE) in Ontario in the first quarter of 2017.[82] This price is compared to a weighted average of the current diesel price of $1.09/litre and current gasoline price of $1.16/litre[83] considering the current diesel/gasoline split of fuel for freight vehicles, 72:28, resulting in a fuel price of $1.11/litre.[84]

The above analysis assumes all commercial freight vehicles are changed out over a twenty year period. We consider the average lifespan for Canada's transportation vehicles to test this assumption. The age distribution of the freight vehicles in Canada for 2009 is shown below (no more recent data is available):[85]

Table 3: Canadian Vehicles - Medium and Heavy Trucks – Age in 2009

	Percentage	**Number**
Less than 3 years	20.6	155,575
3 – 5 years	223	168,413
6 – 9 years	18.1	136,317
More than 9 years	39.1	294,912
TOTAL	**100.0**	**755,217**

Source: Canada, Natural Resources Canada, "Canadian Vehicle Survey – 2009 Summary Report," (Ottawa, 2011). http://publications.gc.ca/collections/collection_2012/mcan-nrcan/M141-18-2009-eng.pdf

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[80] Muhammad Imran Khan, Tabassum Yasmin, and Abdul Shakoor, "International experience with compressed natural gas (CNG) as environmentally friendly fuel," *Energy Systems*, (2015), Vol. 6, Issue 4, pp. 507-531. Retrieved from http://link.springer.com/10.1007/s12667-015-0152-x

[81] Go With Natural Gas, "Comparing Natural Gas to Diesel – Energy Content, What You Need to Know," Accessed 2017-07-15. Retrieved from http://www.gowithnaturalgas.ca/wp-content/uploads/2014/11/Energy-Content-Factsheet-FINAL-EN.pdf

[82] Canada, Ontario Ministry of Energy, "Fuel Prices," Accessed 2017-07-15. Retrieved from http://www.energy.gov.on.ca/en/fuel-prices/?fuel=CNG&yr=2017

[83] Canada, Statistics Canada, "Average Retail Prices for Gasoline and Fuel Oil, By Urban Centre," date modified August 18, 2017, http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=3260009

[84] Canada, Natural Resources Canada, "Energy Resources Data Handbook Tables."

[85] Canada, Natural Resources Canada, "Canadian Vehicle Survey – 2009 Summary Report," p.28.

Based upon the distribution above, the assumption of a twenty year span in which to replace vehicles is reasonable. Assuming a twenty year period and 755 thousand vehicles, 38 thousand vehicles are changed out per year.

2.2.2 Analysis

In order to achieve significant GHG emissions reduction from Canada's fleet of freight transportation vehicles, a replacement of the fleet to compressed natural gas (CNG) or liquified natural gas (LNG) is proposed. CNG and LNG are known technologies currently in use in millions of buses and freight vehicles in over 90 countries. Major implementers include China, India, Pakistan, Iran, Argentina, Brazil and Italy.[86]

Abatement capital costs include the replacement of the entire fleet through twenty years, spread out evenly in that time period. Operating cost savings are applied throughout the entire twenty years, assuming the rate increase, inflation and discount rate noted earlier. Abatement costs are detailed in **Error! Reference source not found.**.

Over a twenty-year period, $85 billion Cdn incremental costs over the market price of diesel freight vehicles is required. When discounted, the net present value of these costs is $51 billion Cdn. The fuel cost savings per year is $3.9 billion Cdn, net present value. Relative benefits are small compared to upfront capital costs. Very simplistically, this implies a payout of thirteen years, a substantial period.

On a per unit basis, the capital inensity of abatement is $39 per tonne of carbon, while the abatement cost is a savings of $345 per tonne.

The reduction in GHG emissions is estimated at 11 tonnes per year, representing 14% of the 2017 estimated emissions from freight vehicles.

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[86] Muhammad Imran Khan, Tabassum Yasmin, and Abdul Shakoor, "International experience with compressed natural gas."

Table 4: Estimated Abatement Costs: Freight Vehicles

	BAU	Natural Gas Freight Vehicles
Project Life	20	20
I. Capital Costs (vehicle purchase costs)		Assumed $58,000 higher for heavy duty vehicles, 31% higher than average price for medium and light vehicles; average 2017 price = $43,778
Total Capital Costs Above BAU (millions $Cdn)	$ -	$ 85,093
Incremental Capital Costs, Net Present Value (millions $Cdn)		$ 50,974
II. Operating Costs per year		
Vehicle-km – (millions) 2017 estimate	139,352	139,352
Average 2017 Fuel Efficiency, l/100 km[1]	27.3	31.0
Estimated emissions, gm CO_2eq/l	549	468
BAU fuel price, $/litre[2]	$ 1.11	
New fuel price, $/GLE (gasoline-litre equiv.)[3]		$ 0.86
Annual Fuel Costs, Net Present Value[4] (millions $Cdn)	$ 31,302	$ 27,399
Annual Operating Costs Above BAU per year, Net Present Value (millions $Cdn)		-$ 3,903
CO_2eq Mt/yr	77	65
CO_2eq Reduction, Mt/yr		11
Abatement Costs, Capital - $/t CO_2		**$ 39**
Abatement Costs, opex - $/t CO_2		**-$ 345**

1. Source: Canada, Natural Resources Canada, “Energy Use Data Handbook Tables,” retrieved 2017-07-07. http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm
2. Average April 2017 gasoline price = $1.16/litre, diesel price = $1.09/l, weighted average to fuel mix seen for freight in 2014. Source = Statistics Canada.
3. Source: May 2017 CNG retail price. http://www.energy.gov.on.ca/en/fuel-prices/?fuel=CNG&yr=2017
4. NPV = 20 year project life, 1.7% annual inflation, 8% discount rate

2.2.3 Policy Recommendations

Currently Canada has heavy duty vehicle and engine GHG emissions regulations in place that set GHG emissions limits for vehicle manufacturers and importers, gradually reducing the maximum level for the fleet.[87] Following this path, technology is gradually changing to adjust to

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[87] Canada, Environment and Climate Change Canada, “Guidance document – Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations,” last updated August 7, 2017, accessed August 7, 2017. http://www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=71EF09D7-1&offset=6&toc=show#s_f_5_2_1

marginally lower targets per year. From 1990 to 2014, the grams of CO_2e GHG emissions per tonne-kilometre fell by 25%. From 2017 onward, the limit is constant, providing little pressure to generate continued improvement. The implementation of a regulated changeover of the entire fleet to CNG would introduce a step-change in efficiency above what can be currently achieved with gasoline and diesel engines. Policy would need to be developed to incentivize industry to make these large-scale changes. Currently the most common arguments against changeover to natural gas freight vehicles are the higher capital cost up front and the lack of retail outlets to source fuel.

Per capita energy demand for freight transport and its associated GHG emissions have continued to increase in Canada over the last twenty-five years, as in many other International Energy Agency (IEA) member countries.[88] Potential policies complementary to the carbon tax include increased road-use fees on truck use, congestion fees, and stimulation of low-carbon-fuel technology areas.[89] The direct tie between GDP and freight volumes with their related GHG emissions is strong.[90] Any policy instruments in the long term must carefully balance the improvement in GHG emissions with the potential impact on GDP.[91]

Pros:

Natural gas as a fuel emits from 10 to 25% lower GHG emissions than burning diesel or gasoline.[92] Natural gas is expected to be priced at a large discount to oil in the long term,[93]

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[88] J. Eom, L. Schipper, L. Thompson, "We keep on truckin': Trends in freight energy use and carbon emissions in 11 EIA countries," *Energy Policy*, (2012), Vol. 45, pp. 327-341. http://linkinghub.elsevier.com/retrieve/pii/S0301421512001577

[89] L. Schipper, L. Scholl, S. Price, "Energy use and carbon emissions from freight in 10 industrialized coutnries: An analysis of trends from 1973 to 1992," *Transportation Research Part D: Transport and Environment*, (1997), Vol. 2, Issue 1, pp. 57-76. http://linkinghub.elsevier.com/retrieve/pii/S1361920996000144

[90] J. Eom, L. Schipper, L. Thompson, "We keep on truckin'."

[91] J. Eom, L. Schipper, L. Thompson, "We keep on truckin'."

[92] Aditya Iyer, "Natural Gas for Transportation: An Affordable Way to Reduce Canada's GHG Emissions," Canadian Natural Gas Vehicle Alliance, (2016). http://www.cngva.org/media/56871/cngva_-_government_relations_and_outreach.pdf

[93] Tiffany Groode, "Natural Gas in On Road Transportation – Stanford Natural Gas Initiative," IHS Energy, San Francisco, (2016). https://ngi.stanford.edu/sites/default/files/7_Groode_IHS.pdf

resulting in a fuel cost advantage of roughly 23 to 40%.[94] In addition to having lower GHG emissions, natural gas produces extremely low levels of NO_x, SO_x, and reduced particulate matter compared to diesel or gasoline.[95] Natural gas engines are substantially quieter than their diesel counterparts when operating.[96] Studies show a general competitiveness with diesel fleet maintenance costs.[97] In recent years, fuel efficiency in natural gas engines has improved considerably also.[98] Twenty three new natural gas fueling stations were built in Canada in 2013 and 2014.[99] This network is gradually growing, and Canada currently has 80 CNG fueling stations.[100]

Cons:

As noted earlier, a primary challenge for changeover to heavy duty natural gas vehicles is the incremental capital cost.[101] Simple payout of incremental capital costs for a natural gas vehicle depends on regional fuel prices and annual mileage. Edelstein estimated payout times typically ranging from 1.4 to 4 years,[102] however Laughlin and Burnham assumed a smaller fuel price differential and lower annual mileage, resulting in payout estimates from 10 to 23 years.[103]

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[94] Aditya Iyer, "Natural Gas for Transportation: An Affordable Way."; Mitch Carlson, "Natural Gas as a Transportation Fuel – Properties, Benefits, & SaskEnergy Support," SaskEnergy, (Regina, 2015). http://www.gowithnaturalgas.ca/wp-content/uploads/2015/01/Natural-Gas-As-Transportation-Fuel.pdf

[95] Ibid.

[96] Canada, Natural Resources Canada, "Natural Gas Use in the Canadian Transportation Sector – Deployment Roadmap," Natural Gas Use In Transportation Roundtable, (2010). https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/transportation/alternative-fuels/resources/pdf/roadmap.pdf

[97] Aditya Iyer, "Natural Gas for Transportation: An Affordable Way."

[98] Ibid.

[99] Mitch Carlson, "Natural Gas as a Transportation Fuel."

[100] Canadian Natural Gas Vehicle Alliance, "Natural Gas Refuelling Stations," Accessed July 15, 2017. Retrieved from http://www.cngva.org/en/home/vehicles-stations/natural-gas-refuelling-stations.aspx

[101] Michael Laughlin and Andrew Burnham, "Case Study – Natural Gas Regional Transport Trucks," U.S. Department of Energy, (2016). https://www.afdc.energy.gov/uploads/publication/ng_regional_transport_trucks.pdf

[102] Stephen Edelstein, "Why Aren't Natural Gas-Powered Long-Haul Semi Trucks Selling Better?", *Green Car Reports*, (2014). http://www.greencarreports.com/news/1094087_why-arent-natural-gas-powered-long-haul-semi-trucks-selling-better; John Smith, "A Price on Carbon, but Support for Natural Gas?" *Today's Trucking*, (2016). https://m.todaystrucking.com/a-price-on-carbon-but-support-for-natural-gas; Mitch Carlson, "Natural Gas as a Transportation Fuel."

[103] Michael Laughlin and Andrew Burnham, "Case Study – Natural Gas Regional Transport Trucks."

Concerns exist regarding the longer lead time when purchasing natural gas vehicles compared to equivalent diesel heavy duty trucks, as there is less demand and a perceived limited supply at this time.[104] A consistent price differential from diesel versus natural gas is also required, and natural gas price volatility is a concern held by some.[105]

The lack of filling stations and the cost of a new refueling infrastructure is also noted as a barrier to wholesale uptake of natural gas vehicles. Filling stations are estimated to cost between $2.7 and $3.4 million Cdn (2017 dollars),[106] a substantial investment. Currently there are over 12,000 retail and commercial gasoline and diesel sales outlets in Canada, employing over 81,000 Canadians.[107] There are an estimated 220 truck fuel stations in Canada;[108] to match that figure with CNG stations eventually, capital investment by fuel providers would be over $400 million Cdn for an additional 140 fuel stations. While a large investment, this only represents an additional 0.5% in capital investment, but it does fall on the shoulders of a different stakeholder group, that of fuel retailers.

Political and Social Feasibility

Coordination between the various levels of government, the consumer, the fuel provider and the vehicle provider, is required when going forward with this suggested strategy.[109] Japan introduced CNG vehicles in Tokyo with two large companies being the primary users, but did

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[104] Ibid.

[105] "Natural Gas Isn't Going to Replace Diesel Fuel," *Hart Energy -Global Refining & Fuels Report*, (2014). https://search-proquest-com.ezproxy.lib.ucalgary.ca/docview/1530205664?pq-origsite=summon

[106] John Smith, "A Price on Carbon, but Support for Natural Gas?"; Michael Laughlin and Andrew Burnham, "Case Study – Natural Gas Regional Transport Trucks."

[107] "The Fuels Industry, What you need to know about our industry." Canadian Fuels Association, accessed 2017-08-29. http://www.canadianfuels.ca/The-Fuels-Industry/

[108] Truckstop Canada, Truckstop Guide, http://www.truckstopcanada.ca/, Husky Road Solutions, http://www.huskyroadsolutions.com/cardlock-network-expansion.html?gclid=Cj0KCQjwoZTNBRCWARIsAOMZHmHT0u7fbtcdfY3MALJzYmBJ58_bYPnfTSpc3f_WqaZHw6a_RZoyyDsaAj6fEALw_wcB; Canada Transportation, Truck Stops Directory. http://www.canadatransportation.com/Truck_stops_MAA.htm

[109] M. Yarime, "Public coordination for escaping from technological lock-in: its possibilities and limits in replacing diesel vehicles with compressed natural gas vehicles in Tokyo," *Journal of Cleaner Production*, (2009), Vol. 17, Issue 14, pp.1281-1288. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0959652609001115

not coordinate well with either the manufacturer or the fuel station providers, resulting in poor uptake and higher costs than anticipated.[110] Canada has worked on this aspect of implementation already, with a road map already outlined.

In 2010, the Natural Gas Use in Transportation Roundtable was initiated, and produced the final report *Natural Gas Use in the Canadian Transportation Sector – Deployment Roadmap* (the "Deployment Report") in December of that year.[111] This report is the product of a multi-stakeholder group including government, fuel providers, vehicle manufacturers and consumers, and results in specific recommendations of go-forward steps. The report considers an overview of natural gas vehicles in general, and based upon its work, recommends in the near term that the focus should be primarily on medium and heavy-duty applications. More substantial barriers to implementation in light duty vehicles, marine and rail applications are seen, therefore the specific go-forward plan within the report zooms in primarily on the medium and heavy transport fields at this time.

The Deployment Report analyzes the potential market failure mechanisms to explain why natural gas vehicles have so little uptake. Weaknesses in the market include perceived risks of entering the market, imperfect information adding further risk to the business decision, lack of choice regarding equipment and fuel sources, and externalities, that is, climate change and other pollution impacts. Four main recommendations are made: first, policies to encourage early adoption through de-risking are recommended. This may include temporary fiscal measures that can serve to reduce perceived risk of end-users of vehicles, and of retailers in fuel sales locations. The second recommendation focuses on an outreach and education strategy, aimed at multiple contact points in the stakeholder group – end-users, fuel retailers, and others in the value chain.

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[110] Ibid.

[111] Canada, Natural Resources Canada, "Natural Gas Use in the Canadian Transportation Sector."

The report's third recommendation focuses on formation of an umbrella organization to develop safety codes and standards, training materials for stations, vehicle repairs, fleet operation and tank inspection, and to serve as a forum for stakeholder discussions of current issues. The final recommendation aims at R&D activities and a focus on future R&D to continue to reduce any cost differential between diesel and natural gas vehicles and maximize natural gas vehicles' long term operational, economic, and environmental benefits.

The Canadian Natural Gas Vehicle Alliance (CNGVA) promotes natural gas transportation as part of Canada's GHG emissions reduction effort. In 2016, the CNGVA submitted budget recommendations to the federal government, including recommendations of allocation of incentives to de-risk some of the upfront costs, allocation of funds for related infrastructure, and provision of some certainty of the current federal fuel tax exemption on natural gas as a transport fuel at least until natural gas achieves a significant share of the market.[112] The 2017 budget includes various items that pertain to these requests. The Low Carbon Economy Fund, the Clean Fuel Standard, and the Canada Infrastructure Bank all generally focus on improving low carbon transportation for Canadians through R&D funding and investment funding.[113] In addition, there is a small amount of funding earmarked for heavy duty vehicle retrofitting over a five-year period.[114]

Historical natural gas fuel usage for freight vehicles in Canada is shown in Figure 4.[115] The blue line indicates the percentage of fuel for freight vehicles in Canada that has been natural gas historically: it was flat until about 2008 and since then it has grown but is still less than

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[112] Canadian Natural Gas Vehicle Alliance, "Canadian Natural Gas Vehicle Alliance Federal Budget Submission," (August, 2016). https://www.ourcommons.ca/Content/Committee/421/FINA/Brief/BR8398161/br-external/Canadian Natural Gas Vehicle Alliance-e.pdf

[113] Canada, "Budget 2017 – Budget Plan," (2017). http://www.budget.gc.ca/2017/docs/plan/toc-tdm-en.html

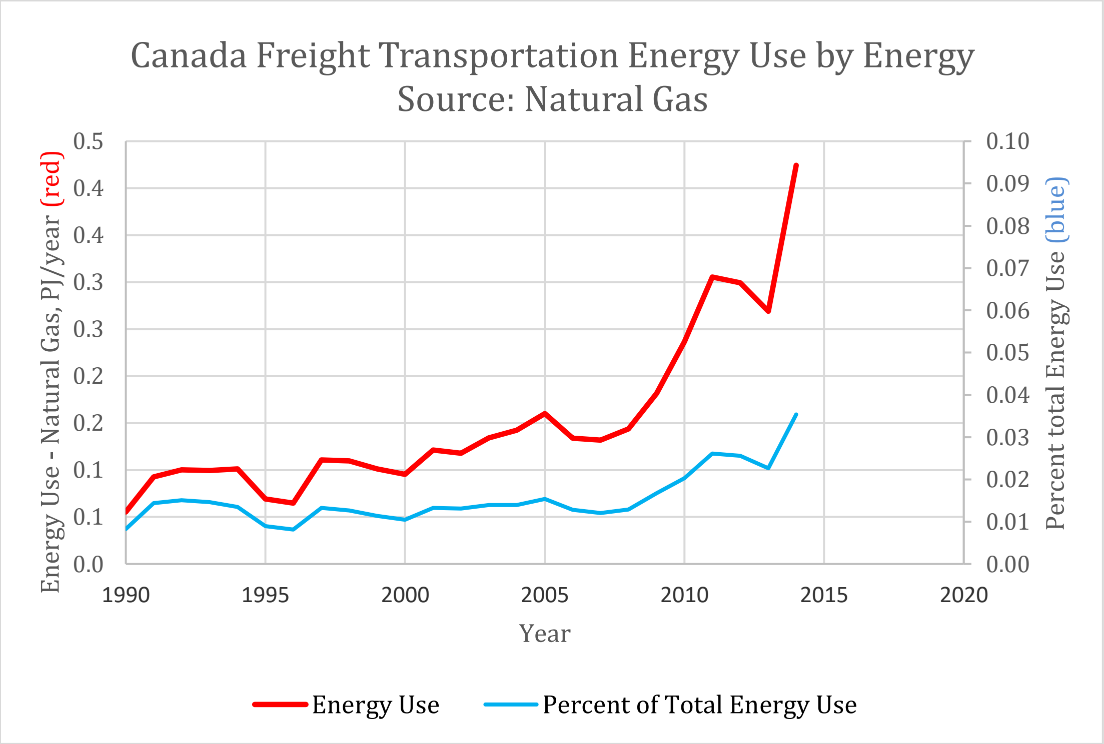
[114] Ibid.

[115] Canada, Natural Resources Canada, "Energy Resources Use Handbook Tables."

0.04%, a tiny fraction of the total market. The red line denotes the amount of energy that entails. Because the freight market has grown consistently with GDP over the years, the natural gas fuel usage (the red line) has grown from 1990 onward, and continues to grow, following a roughly exponential growth curve, albeit starting with very small numbers.

Although the Deployment Report outlines a strategy consistent with removing barriers and roadblocks to encourage additional implementation in the market, policies in general are not aggressively moving the freight fleet over to natural gas. The political and private stakeholder interest is there to open the market further, however the economic drivers still appear weak, with the significant upfront costs still seen as a large barrier to entry. Because the freight sector is tied to GDP growth, it should be a focus area for strategic replacement of diesel fuel with lower emissions natural gas immediately. This policy direction will help to meet Canada's growth goals and its GHG emissions reduction goals at the same time.

Figure 4: Canada Freight Transportation Energy Use by Energy Source: Natural Gas



Data source: Canada, Natural Resources Canada, “Energy Use Data Handbook Tables,” retrieved 2017-07-07. http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

Complementary Policies

The implementation of a carbon tax on all combustion fuels will serve to further incentivize changeover of the freight fleet in Canada to natural gas fuel. However, it does not affect the capital cost requirements. Previously, FortisBC implemented a subsidy program for natural gas commercial fleets in order to attract significant commercial customers with some success.[116] A matching federal program for a limited time period would similarly reduce some of the initial risk. Other potential complementary policies include the introduction of tax incentives upon buying natural gas vehicles, and the introduction of insurance cost reduction programs for natural gas vehicle owners. Exploration of long-term commitments between fleet owners and fuel providers could reduce risks and ensure cost stability also.[117]

3.0 Gas Plant CCS Retrofit: Alberta’s History, Redux

3.1 Assumptions

In 2015, natural gas GHG emissions were 55.6 Mt CO_2e in Canada.[118] This section explores the amount of GHG emissions and associated cost that could be diverted from natural gas production in the oil and gas industry at existing natural gas processing plants. While technology is not yet commercially available for large scale implementation for carbon capture

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[116] Mitch Carlson, “Natural Gas as a Transportation Fuel.”; FortisBC, “Vehicles for Change – Medium and Heavy-duty Fleet Incentives,” accessed August 29, 2017. https://www.fortisbc.com/NaturalGas/Business/NaturalGasVehicles/Howwecanhelp/Incentives/MediumHeavyDutyFleetIncentive/Pages/default.aspx

[117] Masaru Yarime, “Public Coordination for Escaping from Technological Lock-in: its Possibilities and Limits in Replacing Diesel Vehicles with Compressed Natural Gas,” *Journal of Cleaner Production*, (2009), pp. 1281-1288. http://linkinghub.elsevier.com/retrieve/pii/S0959652609001115; Dianne Cardwell and Clifford Krauss, “Natural gas becomes a fuel for the long haul,” *NC Clean Energy Technology Center*, (2012). Retrieved from https://nccleantech.ncsu.edu/natural-gas-becomes-a-fuel-for-the-long-haul/

[118] Canada, Environment and Climate Change Canada, “Greenhouse Gas Emissions.”

and storage at electricity generation sites, CO_2 capture and reinjection has been successfully implemented for 28 years in Canada in conjunction with “sour” gas plants.[119]

In this study, CCS is considered at the pre-combustion stage, in the field where natural gas is gathered and stripped of impurities to reach required fuel quality for markets. At this point in the sour gas processing, CO_2 is at a high concentration, between 15 and 98%, improving the economics of removal and injection.[120] In the case of a coal fired electricity plant, the flue gas will contain approximately 1 to 13% CO_2, and removal will thus be less efficient.[121]

For over sixty years, sour gas plants have operated in Canada,[122] and the first acid gas injection scheme at a sour gas plant was implemented in 1989.[123] Natural gas containing hydrogen sulfide (H_2S) is collected and processed at these plants to remove the H_2S and other impurities before it is put in the sales pipeline and distributed as fuel gas for furnaces and other market uses. In addition to H_2S, CO_2 is also removed by the same process. The “acid gas” stream, comprised of H_2S, CO_2 and other contaminants stripped out of the natural gas stream, has three potential choices for further handling: the gas plants are set up to either flare the acid gas if it is an extremely small amount, recover the sulphur in solid form and vent or flare the remainder, or reinject the entire acid gas stream into a deep geologic formation underground. The

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[119] Sam Wong, David Keith, Edward Wichert, Bill Gunter and Tom McCann, “Economics of Acid Gas Reinjection: An Innovative CO_2 Storage Opportunity,” Alberta Research Council, Edmonton, (2003). Retrieved from https://scholar.harvard.edu/files/davidkeith/files/56.wong_.2003.economicsofacidgasreinjection.e.pdf

[120] Sam Wong, David Keith, Edward Wichert, Bill Gunter and Tom McCann, “Economics of Acid Gas Reinjection.”; P. Hardisty et al, “The Environmental and Economic Sustainability of Carbon Capture and Storage,” *International Journal of Environmental Research and Public Health*, (2011), Vol. 8, Issue 12, pp.1460-1477. Retrieved from http://www.mdpi.com/1660-4601/8/5/1460/

[121] Ron Zevenhoven and Pia Kilpinen, “Flue Gases and Fuel Gases,” Control of pollutants in flue gases and fuel gases, Espoo, (2001). Retrieved from http://users.abo.fi/rzevenho/gases.PDF

[122] Canada, Alberta, Alberta Energy Regulator, **“**ST50A: Gas Processing Plants in Alberta (sorted by gas plant reporting facility ID code) ISSN 0838-1224,” retrieved from https://www.aer.ca/data-and-publications/statistical-reports/st50

[123] Sam Wong, David Keith, Edward Wichert, Bill Gunter and Tom McCann, “Economics of Acid Gas Reinjection.”

choice of process is strictly regulated by the Alberta Energy Regulator, based upon various parameters of the specific application.[124]

Forty-nine facilities are licensed to reinject acid gas in Alberta, and have been executing CCS successfully for many years in order to dispose of H_2S. [125] In addition, many facilities in Alberta capture H_2S and CO_2 but vent the CO_2 later in the process. In B.C., nineteen gas plants are licensed to process sour gas.[126] There are also a number of gas plants that process sweet gas (natural gas with zero H_2S content) and move a large amount of CO_2 within the natural gas stream, where it remains when it goes to become sales gas for the market. Maximum CO_2 concentration in sales gas throughout North America is typically 2.0%.[127]

The calculations here are based on the assumption that current throughput rates for each facility are constant going forward, an average CO_2 concentration of 2.0% by volume exists in sales gas streams, and 100% of the CO_2 is captured and reinjected. As noted earlier, natural gas processing in Canada has varied with time, though total natural gas sales have been relatively flat from 2000 to 2017.[128] Following this trend, we assume gas volumes will be constant over the life of the project. The maximum allowable CO_2 content in most sales gas in North America is 2.0%, therefore this is felt to be a reasonable assumption. In sour gas plants where CO_2 is captured with H_2S in a stripping process using amine solution, typical recoveries of CO_2 may be 99% or greater

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[124] Operators are required to meet certain H_2S recovery standards for varying plant throughput levels, and once the H_2S is stripped out of the gas stream, it may be processed and separated to produce solid sulphur for sale, or it may be reinjected, dependent on the business choice of the operator. All process choices are heavily regulated. See Alberta Energy Regulator for governing regulations. https://www.aer.ca/rules-and-regulations/acts-and-rules

[125] Canada, Alberta, Alberta Energy Regulator, **"**ST50A: Gas Processing Plants in Alberta."

[126] Canada, British Columbia, BC Oil & Gas Commission, accessed 2017-07-17, https://www.bcogc.ca/gas-plant-design-capacities

[127] TransCanada, "TransCanada – Tariff Reference, Gas Quality Specifications," updated May 4, 2011, retrieved July 17, 2017. http://tcplus.com/GTN/GasQualityDataChromatograph/TariffPdf

[128] Canada, National Energy Board, "Marketable Natural Gas Production in Canada," accessed 2017-07-31. https://www.neb-one.gc.ca/nrg/sttstc/ntrlgs/stt/mrktblntrlgsprdctn-eng.html

depending on the solvent used.[129] In these calculations, 100% recovery was used for simplicity; as a result the GHG emissions estimates will be slightly optimistic.

When constructing a new acid gas reinjection facility any power requirements are assumed to be met with electricity. The CO_2 emission factor for power in Alberta is 0.64 kg CO_2e/KWh, effective March, 2015.[130] This figure is used to determine the mitigation efficiency of acid gas reinjection, accounting for CO_2 produced in generating the power required to run the reinjection facility.

CCS costs are estimated here by using the Wong et al estimate[131] and both scaling up and applying inflation to revise to the correct facility size and 2017 dollars. The original estimate was for a gas plant with throughput of 729 thousand cubic metres per day (e3m3/d) raw gas inlet rate and 1.6% CO_2, and the cost estimate was prepared in 2003. In order to scale up and consider a 2017 estimate, we apply the actual inflation rate from 2003 to 2016[132] to the original cost estimate to determine a current 2017 capital cost and operating cost per unit inlet volume. The 2017 estimated cost factors are $335,487/e3m3/d CO_2 inlet for capital costs, and $55,878/e3m3/d CO_2 inlet annual operating costs. These factors are then used in conjunction with the estimated CO_2 volumes to be mitigated, from above. Table 5 below presents the scale-up and inflation calculations.

Table 5: Wong and Wichert Example: CCS Scale-up and Inflation Calculations

Year	**2003[1]**	**2017**
Raw Gas inlet, e3m3/d	729	
Est. CO_2 content, %	1.6	

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[129] Subhasish Mitra, "A Technical Report on Gas Sweetening by Amines," Petrofac Engineering (I) Ltd., (2015) https://www.researchgate.net/profile/Subhasish_Mitra/publication/279298133_A_technical_report_on_gas_sweetening_system/links/5591d11608ae47a34910ba2a/A-technical-report-on-gas-sweetening-system.pdf

[130] Canada, Alberta, "Carbon Offset Emission Factors Handbook," (2015), http://aep.alberta.ca/climate-change/guidelines-legislation/specified-gas-emitters-regulation/documents/CarbonEmissionHandbook-Mar11-2015.pdf

[131] Sam Wong, David Keith, Edward Wichert, Bill Gunter and Tom McCann, "Economics of Acid Gas Reinjection."

[132] Canada, Statistics Canada, "Consumer Price Index, historical summary," CANSIM table 326-0021, (Ottawa, 2017), last revised January 20, 2017, accessed August 29, 2017. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm

Est. CO_2 flowrate, e3m3/d	11.7	
Acid Gas Compressor Power Consumption, kW	108	
CO_2 cost from Power Consumption, expressed as mitigation efficiency[2]	82%	
Average annual inflation rate, 2003 to 2016, %[3]	1.8	
Capital Costs, $Cdn	**2003 $**	**2017 $**
Injection well	$800,000	$1,026,973
Compressor package	$1,500,000	$1,925,574
Acid gas dehydration package	$500,000	$641,858
Pipelining and control	$250,000	$320,929
TOTAL	$3,050,000	$3,915,333
Total Capital Costs per e3m3/d CO_2 Flowrate	**$261,341**	**$335,487**
Operating Costs, $Cdn per year		
Financing costs	$358,000	$459,570
Op expenses	$150,000	$192,557
TOTAL	$508,000	$652,128
Total Operating Costs per e3m3/d CO_2 Flowrate	**$43,528**	**$55,878**

1. From Wong et al: S. Wong, D. Keith, E. Wichert, et al, "Economics of Acid Gas Reinjection: An Innovative CO_2 Storage Opportunity," Alberta Research Council, Edmonton, (2003). Retrieved from https://scholar.harvard.edu/files/davidkeith/files/56.wong_.2003.economicsofacidgasreinjection.e.pdf

2. Power usage = 88% is the efficiency in Wong et al, assumes an older CO_2 emission factor.

3. Assumed 1.8% annual inflation rate - Source = Canada, Statistics Canada, "Consumer Price Index, historical summary," CANSIM table 326-0021, (Ottawa, 2017), last revised January 20, 2017, accessed August 29, 2017. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm

The Wong et al case is also used to estimate power requirements for the acid gas reinjection compression, and to determine the mitigation efficiency.

3.2 Analysis

Gas sales volumes for the first quarter of 2017 in Canada are used in estimating potential CO_2 volumes that could be captured. As actual single gas plant throughput volumes are not known, an overall proration factor was calculated based upon total plant capacity versus total sales volumes. Using a 2.0% CO_2 content, the potential CO_2 volume that could be separated and reinjected is estimated. In the first quarter of 2017, natural gas production in Canada averaged

15.8 billion cubic feet per day (BCFD).[133] Approximately 33% of the gas produced in Canada contains H_2S before processing.[134]

Column A in Table 6 indicates the amount that is currently being sequestered and reinjected, approximately 0.2 Mt CO_2e/yr. If all other gas processing facilities are considered that capture acid gas including CO_2, but normally vent it after dealing with the related H_2S content, an additional estimated 1.6 Mt/year CO_2 could be captured and sequestered (Column B). Significant CO_2 exists in the sweet gas in Alberta and B.C. also. If we consider all the sweet gas plants in Alberta and B.C. and assume an average 2.0% CO_2 content in the gas throughput, an additional 2.5 Mt/year could be sequestered (Column C):

Table 6: Estimate of CO2 Volumes for Potential Sequestration

	A. Existing Acid Gas Reinjection Facilities	**B.: Acid Gas Currently Not Sequestered**	**C. CO_2 From All Sweet Gas Plants**
Current Sales - Q1 2017(MMCFD)	504	3,877	6,203
Current Sales - Q1 2017 (e3m3/d)	14,248	109,535	175,248
CO_2 mol mass, g/mol	44.01	44.01	44.01
Density of CO_2, kg/m3 at standard conditions	1.98	1.98	1.98
Estimated CO_2 %, volume	2.00	2.00	2.00
CO_2. Rate, MMCFD	10	78	124
CO_2. Rate, e3m3/d	285	2,191	3,506
Potential CO_2 per day injected, kg/day	564,426	4,339,156	6,942,318
Potential CO_2 injected, Mt/year	**0.2**	**1.6**	**2.5**

Below is the cost estimate for the construction and operation of the two additional CCS applications noted above in Case B. and Case C., using the Wong et al scale-up and inflation factors. Capital costs are 2017 dollars, while the net present value of operating expenses are

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[133] Canada, National Energy Board, "Marketable Natural Gas Production in Canada."

[134] Canada, Alberta, Alberta Energy Regulator, "ST50A: Gas Processing Plants in Alberta," accessed 2017-07-17, https://www.aer.ca/data-and-publications/statistical-reports/st50; Canada, British Columbia, BC Oil & Gas Commission, "Gas Plant Design Capacities," accessed 2017-07-17, https://www.bcogc.ca/gas-plant-design-capacities; Canada, Saskatchewan, "Gas Plant Report," accessed 2017-07-17, http://publications.gov.sk.ca/deplist.cfm?d=310&c=5376

calculated assuming inflation of 1.7% per year and discounted at eight percent for the life of the project.

The power requirements for the acid gas reinjection compression and the mitigation efficiency are determined next. The power requirement from the original Wong and Wichert report is 108 kW for a CO_2 flowrate of 11.7 e3m3/d. We scale this up for case in which the acid gas not currently sequestered with a CO_2 flowrate of 2,191 e3m3/d and the power requirement is therefore (2,191/11.7 x 108) or 20,225 kW. The corresponding CO_2 flowrate in tonnes per day equals 4,339 t/d. Given the power rating and the CO_2 flowrate, the power consumption of the acid gas compressor would be (20,225 x 24/4,339) or 112 kWh/t of CO_2 compressed. Using the current Alberta CO_2 emission factor for average electricity generation in Alberta of 0.64 kgCO_2/kWh[135] and a transmission efficiency of 90%, the CO_2 emitted from electricity running the acid gas compression would be (112 x 0.64 / 0.9) or 80 kg CO_2/t of CO_2 compressed. For every tonne of CO_2 compressed and injected, 80 kg or 0.080 tonnes is generated through the compression. This can be translated into a mitigation efficiency of (1 – 0.080) x 100 or 92%:

Table 7: Estimated CCS Facility Costs

	B. Install Acid Gas Injection Facilities at Existing Sour Gas Plants that Currently Vent CO_2	**C. Install CO_2 Capture and Acid Gas Injection Facilities At All Alberta and B.C. Sweet Gas Plants**
Assumed project life, years	20	20
Raw Gas Inlet, e3m3/d	109,535	175,248
Raw Gas Inlet, MMCFD	3,877	6,203
Estimated CO_2 Content, %	2.0	2.0
Estimated CO_2 Rate, e3m3/d	2,191	3,505
Estimated CO_2 Rate, MMCFD	78	124
Target CO_2 Sequestration, Mt/year	1.6	2.5
CO_2 Sequestration, with Mitigation Efficiency Applied - Mt/year	**1.5**	**2.3**
Facilities Required:	All acid gas injection equipment noted by Wong et al	All acid gas injection equipment noted by Wong et al, plus amine stripping equipment[1]

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[135] Canada, Alberta, "Carbon Offset Emission Factors Handbook," (2015), http://aep.alberta.ca/climate-change/guidelines-legislation/specified-gas-emitters-regulation/documents/CarbonEmissionHandbook-Mar11-2015.pdf

Estimated Capital Costs, net present value $Cdn	$734,953,580	$1,763,804,430
Estimated Annual Op Costs, net present value $Cdn	$75,227,140	$180,536,522
Abatement Costs, Capital - $/t CO_2	**$25**	**$38**
Abatement Costs,[2] Opex - $/t CO_2	**$52**	**$77**

1. Estimated additional 50% for capital and op costs for amine stripping equipment
2. Future operating expenses inflated at 1.7% (Statistics Canada average from 2010 to 2016), and discounted at 8% for life of project

Combining total capital and operating abatement costs for the case in which acid gas is not currently sequestered, the cost is $77/t CO_2. The 2017 SCC range is $44.23 to $181.96/t CO_2e. If the cost of carbon is internalized in this range, it could incentivize gas plant owners to implement acid gas injection equipment and sequester the additional volumes noted above.

3.3 Policy Recommendations

CCS is a pragmatic response to global warming that aids in dealing with a major environmental issue of the day while retaining a standard of living.[136] The CO_2 figures that can be captured and sequestered from existing sour gas plants total 1.5 Mt/yr, approximately 2.7% of the total GHG emissions from natural gas production in Canada. The total amount of CO_2 that could be sequestered from all sweet gas plants in Canada is estimated at 2.3 Mt/yr, representing another 4.1% of the total GHG emissions from natural gas production in Canada. While small, these numbers could be seen as a pilot project in moving carbon capture technology forward commercially.

The use of a pilot project such as the current acid gas injection schemes to lay the groundwork and reduce multiple barriers for CCS projects is recommended.[137] Risk management

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[136] Anders Hansson and Marten Bryngelsson, “Expert opinions on carbon dioxide capture and storage – A framing of uncertainties and possibilities,” *Energy Policy*, (2009), Vo. 37, Issue 6, pp.2273-2282. Retrieved from http://www.sciencedirect.com.ezproxy.lib.ucalgary.ca/science/article

[137] Phil Hare et al, “April 2015 Potential CCS Cost Reduction Mechanisms: Final Report,” Committee on Climate Change (UK), (2015). https://d2kjx2p8nxa8ft.cloudfront.net/wp-content/uploads/2015/06/Pöyry-Element-Energy2015-Potential-CCS-Cost-Reduction-Mechanisms-Report.pdf

is a key issue, including technical, financial and business risk.[138] The successful development of salient, high profile pilot projects can help defray risks for larger projects going forward.

Main stakeholders include gas plant owners. Given the consistently low natural gas prices since 2009, there is little incentive for these additional capital investments to be made unless regulated and incentivized to do so. In addition, there are over 500 sweet gas plants in Canada and this would entail significantly more capital investment compared to the sour gas plants, since H_2S and CO_2 are already sequestered at all the sour locations.

Because of the significant up-front capital costs, the focus of these costs on a small stakeholder group, and the fact that a number of other measures listed here have much more beneficial abatement costs (benefits), it is not recommended these abatement projects be pursued by government. Abatement measures that are financially beneficial to large quadrants of the population are more palatable than those that cost significant funds and result in negative cash flow to some parties.

Pros

The stripping process used to remove H_2S and CO_2 in most sour gas plants is the same process utilized in CCS applied to post-combustion at power generation plants.[139] By implementing carbon storage at the remaining sour gas plants in Alberta that already capture high concentration CO_2, the additional projects will validate the integrity of geologic storage, in addition to serving as a place for research and development to continue to reduce costs of the

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[138] Ibid.

[139] Jon Gibbins and Hannah Chalmers, “Carbon Capture and Storage,” *Energy Policy*, Vol. 36, Issue 12, (2008), pp. 4317-4322. http://www.sciencedirect.com.ezproxy.lib.ucalgary.ca/science/article/pii/S0301421508004436

applicable technologies.[140] Regulations in Alberta and B.C. are already in place to facilitate acid gas reinjection, allowing for quicker implementation compared to power plant applications.[141]

Cons

The main barriers of CCS application in general are the lack of funding mechanisms, combined with limited legal and regulatory frameworks to date.[142] As noted above, regulations regarding acid gas reinjection specifically are already in place and have been utilized for 28 years, reducing this issue. However, project operators need to see an incentive for reducing CO_2 emissions, or legislation imposing CCS will be required. [143] The instances where it is in place now represent the best economic choice by the operator at the time of construction, when meeting the regulatory needs of capturing the H_2S in the gas streams. Economics and regulations will be the first drivers necessary to incentivize broader CCS use.[144]

The concept of removing CO_2 from the natural gas stream at sweet processing plants in Canada is on different ground than that of sour plants. CO_2 has not been typically considered a contaminant, and is found in sales gas streams at a relatively low concentration. With respect to these sweet plants, it is expected regulations imposing CCS requirements will serve to push cash flows under water or close to it, and result in shutting in of gas volumes, rather than face the high capital requirements of CCS. It is therefore not a recommended go-forward policy initiative.

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[140] National Commission on Energy Policy, “The 10-50 Solution: Technologies and Policies for a Low-Carbon Future,” Pew Center/NCEP Workshop on the 10-50 Solution, Washington, (2004). https://www.c2es.org/docUploads/10-50_Full Proceedings.pdf

[141] Canada, Alberta, Alberta Energy Regulator, “Acts, Regulations, & Rules,” https://www.aer.ca/rules-and-regulations/acts-and-rules

[142] Jon Gibbins and Hannah Chalmers, “Carbon Capture and Storage.”

[143] Ibid.

[144] Ibid.

Political and Social Feasibility

The 2016 International Energy Agency report “20 Years of Carbon Capture and Storage”[145] summarizes the slow progress in development of commercial CCS since it was recognized in 2005 as a critical part of a plan in dealing with climate change.[146] Projects have been planned but not implemented due to fluctuating policy and financial support, and many early CCS plans proved to be more complex, expensive and politically challenged than previously thought.[147]

Market fluctuations seen from 2005 to present have added uncertainty to the long-term funding required in such large-scale projects.[148] With the current weak natural gas market in Canada, large incentives will be required to engage industry to implement further CCS at existing sour plants.

In 2007, the Alberta government partnered with the federal government and formed the Task Force on Carbon Capture and Storage.[149] The task force was comprised of industry, academic, and government representatives. In their report issued in early 2008, the general concept of substantial funding of CCS technologies was outlined as a means by which the country could increase its oil and gas production while reducing its GHG emissions. Through the joint government/industry work, goals were laid out including a first wave of industrial CCS facilities, and clarification of disposal rights and liability solutions.[150] Government investment

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[145] “20 Years of Carbon Capture and Storage – Accelerating Future Deployment,” International Energy Agency, Paris, (2016). https://www.iea.org/publications/freepublications/publication/20YearsofCarbonCaptureandStorage_WEB.pdf

[146] “IPCC Special Report on Carbon Dioxide Capture and Storage,” Intergovernmental Panel on Climate Change, New York, (2005). https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

[147] “20 Years of Carbon Capture and Storage – Accelerating Future Deployment.”

[148] Ibid.

[149] Canada, Natural Resources Canada, The ecoENERGY Carbon Capture and Storage Task Force, “Canada’s Fossil Energy Future-The Way Forward on Carbon Capture and Storage,” (2008). https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/www/pdf/com/resoress/publications/fosfos/fosfos-eng.pdf

[150] Ibid.

since then has included a number of projects including the Alberta Carbon Trunk Line, [151] and the Shell Canada Energy Quest Project.[152]

Continued steady funding for CCS, including expansion into current sour gas plants, is recommended.[153] In addition, further education and public communications are recommended in order to continue to build the groundwork between government, industry, and the public regarding CCS applications in Canada. In 2010, the Barendrecht CCS project proposed in the Netherlands was cancelled due to public outcry, with one of the main reasons being poor consultation.[154]

4.0 Residential Retrofits: Small Changes Add Up

4.1 Assumptions

This section determines what Canadians can do in their homes with current technology that is commercially available to lower GHG emissions, in five key areas:

- Installation of high efficiency furnace
- Replacement of all major appliances to Energy Star high efficiency
- Replacement of all lightbulbs to LED high efficiency
- Reduction of hot water heating needs with installation of low-flow shower heads and faucet aerators
- Installation of programmable thermostat

Canada has already made significant progress in many of these areas. The baseline average will therefore include that progress. For example, 37% of households in Canada in 2011

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[151] Canada, Alberta, "Alberta Carbon Trunk Line," Accessed 2017-08-20. http://majorprojects.alberta.ca/Details/Alberta-Carbon-Trunk-Line/622

[152] Shell Canada, "Quest Carbon Capture and Storage," accessed 2017-08-20. http://www.shell.ca/en_ca/about-us/projects-and-sites/quest-carbon-capture-and-storage-project.html

[153] "20 Years of Carbon Capture and Storage – Accelerating Future Deployment."

[154] C. Feenstra, T. Mikunda, S. Brunsting, "What Happened in Barendrecht?" Energy Research Centre of the Netherlands, Global CCS Institute, (2010). http://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/8172/barendrecht-ccs-project-case-study.pdf

had a programmable thermostat installed, and 90% have at least one low-flow showerhead. Nonetheless, there is still significant room to improve in these areas.

This section determines the amount of GHG emissions reduction achievable through all Canadian households changing to current low energy choices that are common and commercially available. A baseline of the current level of efficiency is used, based on the latest Statistics Canada census and its results regarding energy efficiency choices to date. After quantifying the estimated GHG emissions reductions achievable, the potential cost and savings are calculated based on current consumer energy prices in Canada.

Canada is comprised of 15,412,443 households (2016).[155] Average 2014 annual household energy use was 112 GJ (gigajoules) per household.[156] Of this number, 64% was used for space heating, 19% for water heating, 12% for appliances, and 3% for lighting.[157] The 2011 census provides the most recent data regarding energy savings progress for Canadian households, and shows many households have already started the transition.[158] This is the baseline with which to compare, using the percentage uptake determined from this survey, and applying to current household numbers (Table 8).[159]

Table 8: Baseline Canadian Household Energy Efficiency Data - 2011

Appliances: Percentage That Are Energy Star (high efficiency)	Percent
Refrigerator	48
Freezer	34
Dishwasher	50
Washer	51
Average	46
(Range and Dryer not listed with Energy Star in StatsCan)	

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[155] Canada, Statistics Canada, “Population And Dwelling Count Highlight Tables, 2016 Census,” (2017), http://www12.statcan.ca/census-recensement/2016/dp-pd/hlt-fst/pd-pl/Table.cfm?Lang=Eng&T=101&S=50&O=A

[156] Canada, Natural Resources Canada, “Energy Use Data Handbook Tables.”

[157] Ibid.

[158] Canada, Statistics Canada, Environment Accounts and Statistics Division, “Households and the Environment: Energy Use,” (2011). http://www.statcan.gc.ca/pub/11-526-s/2013002/tablesectlist-listetableauxsect-eng.htm

[159] Ibid.

Percentage with programmable thermostats that are programmed	37

Light bulbs - Average Number of Bulb Types per household	
Number of incandescent light bulbs	12
Number of compact fluorescent light bulbs	10
Number of halogen light bulbs	9
Number of fluorescent tubes	11
Total	41

Percentage of furnaces that are high efficiency	25
Percentage of households with at least one lowflow showerhead	90

Home Heating Systems – Percentage Distribution by Type	
Furnaces - total	52
Boilers - total	9
Electric baseboards - total	26
Other	12

Source: 2011 Survey of Household Energy Use (SHEU-2011) Data Tables, http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/sheu/2011/tables.cfm

Energy use for Canada and for an average Canadian household in the BAU case is detailed in Table 9.[160]

Table 9: Current Energy Use in Canada - 2014

Current Energy Use: BAU Case		
Home Heating – per household	71.2	GJ per year
Major Appliances - per household	7.8	GJ per year
Home Water Heating – per household	21.4	GJ per year
Home Lighting - per household	3.8	GJ per year
Home Heating - Canada	997	PJ per year
Major Appliances - Canada	112	PJ per year
Home Water Heating - Canada	300	PJ per year
Home Lighting - Canada	54	PJ per year

Source: Natural Resources Canada - Energy Use Data Handbook Tables - http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

In estimating the amount of energy saved for each item and therefore the related GHG emissions reductions, first a baseline is considered using Statistics Canada data describing the

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[160] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

average Canadian household, noted above. Then changeover of the lightbulbs, appliances and other items that are not already energy efficient is assumed. Energy savings and costs are estimated for one average household and then scaled up for a national estimate.

Households in Canada obtain their energy from various sources including electricity, natural gas, heating oil, wood and propane. Both price and GHG emissions vary with source. The breakdown varies geographically, but for this estimate three average GHG emissions breakdowns are considered: the overall energy breakdown of the average household in Canada, that of the average heating system in a household, and the average energy breakdown for hot water heating in a household. For sectors sourcing energy from the electrical grid, related GHG emissions are estimated by considering the average GHG emissions from electricity generation in Canada (Table 10).[161]

Table 10: Electricity Sector Greenhouse Gas Emissions, Canada, 2010 to 2015

Year	**Coal (megatonnes of carbon dioxide equivalent)**	**Natural gas (megatonnes of carbon dioxide equivalent)**	**Other[1] (megatonnes of carbon dioxide equivalent)**	**Total,[2] Mt CO2eq/year**	**Electricity Generation,[3] TWh**	**GHG Emissions, kg/KWh**
2010	77.4	13.5	4.9	95.8	589	0.163
2011	68.2	16.1	4.3	88.6	618	0.143
2012	63.0	17.6	4.3	84.9	615	0.138
2013	63.7	13.8	4.6	82.1	620	0.132
2014	61.2	13.3	5.0	79.5	639	**0.124**
2015	61.0	12.7	5.1	78.8		

1. The Other category includes diesel fuel oil, heavy fuel oil, light fuel oil, motor gasoline, petroleum coke, own use of primary electricity, solid wood waste and still gas. Totals may not add up due to rounding.
2. Source: Environment and Climate Change Canada (2017) National Inventory Report 1990–2015: Greenhouse Gas Sources and Sinks in Canada (www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=83A34A7A-1).
3. Source of Electricity Data: Natural Resources Canada, About Electricity. Retrieved from http://www.nrcan.gc.ca/energy/electricity-infrastructure/about-electricity/7359

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[161] Canada, Environment and Climate Change Canada, “National Inventory Report 1990–2015: Greenhouse Gas Sources and Sinks in Canada”, (2017), www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=83A34A7A-1; Canada, Natural Resources Canada, “About Electricity.” http://www.nrcan.gc.ca/energy/electricity-infrastructure/about-electricity/7359

Assuming 2014 figures, on average one kilowatt-hour of electrical power in Canada will produce 0.124 kg CO_2, or 34.4 kg CO_2/GJ.[162] For sectors considering natural gas or other single fuels alone as the energy source, emission factors are defined in kilograms per gigajoule energy produced, based upon chemical combustion properties (Table 11). [163]

Table 11: Greenhouse Gas Emission Factors for Various Fuels

	GHG Emissions - kg/GJ
Electricity – average in Canada	34
Natural Gas	56
Oil	77
Wood	110
Propane	63

Source: "Archived – Appendix B – CO_2 Emission Factors," Natural Resources Canada. Accessed 2017-08-29.
http://www.nrcan.gc.ca/energy/efficiency/industry/technical-info/benchmarking/canadian-steel-industry/5193

Canadian households use a mix of energy sources. The average GHG emissions per unit of energy is therefore estimated as follows for general energy use, and displayed in Table 12.[164]

Table 12: Total Household Energy Source Composition – 2014

	% Of Energy Source for All Canada Households	**GHG Emissions - kg/GJ**
Electricity	37	34
Natural Gas	47	56
Oil	5	77
Wood	10	110
Propane	1	63
TOTAL	100	
Average GHG emissions =	**54.6 kg/GJ**	

Source: Natural Resources Canada - Energy Use Data Handbook Tables -
http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

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[162] One gigajoule of energy equals 277.78 kWh.

[163] Canada, Natural Resources Canada, "Archived – Appendix B – CO2 Emission Factors," accessed 2017-08-29. http://www.nrcan.gc.ca/energy/efficiency/industry/technical-info/benchmarking/canadian-steel-industry/5193

[164] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

When estimating the GHG emissions for home heating, the energy source composition is slightly different:[165]

Table 13: Home Heating Energy Source Composition – 2014

	% Of Home Heating Energy Source for All Canada Households	**GHG Emissions - kg/GJ**
Electricity	25	34
Natural Gas	52	56
Oil	6	77
Wood	15	110
Other	2	63
TOTAL	100	
Average GHG emissions =	**60.1 kg/GJ**	

Source Natural Resources Canada - Energy Use Data Handbook Tables - http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

The GHG emissions for home water heating also has a slightly different energy source composition:

Table 14: Home Water Heating Energy Source Composition – 2014

	% Of Home Water Heating Energy Source for All Canada Households	**GHG Emissions - kg/GJ**
Electricity	25	34
Natural Gas	69	56
Oil	3	77
Wood	2	110
Propane	0	63
TOTAL	100	
Average GHG emissions =	**51.8 kg/GJ**	

Source: Natural Resources Canada - Energy Use Data Handbook Tables - http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

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[165] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

These GHG emissions levels per unit energy from 2014 are used when assessing the reduction in energy use, and therefore the corresponding reduction in GHG emissions for each area of household retrofit.

When determining GHG emissions levels and a potential achievable reduction, the cost of energy for residential buildings is used to determine potential cost savings. Average cost for residential electricity in Canada is estimated at $0.124 per kWh from May 2016 data.[166] The natural gas price is estimated at $12.53/GJ from May 2016 data,[167] and the fuel oil price is estimated at $17.23/GJ from June 2017 data.[168] Using the energy source breakdowns noted above and these energy prices, the average energy prices for various residential areas are calculated as follows:

- Home heating average energy cost = $19.13/GJ
- Home water heating average energy cost = $18.30/GJ
- Lights average energy cost = $34.46/GJ
- Appliances average energy cost = $34.46/GJ

These prices will be used to estimate energy cost savings that are realized in conjunction with GHG savings.

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[166] Manitoba Hydro, “Energy Rates and Options, Utility Rate Comparison,” price effective May 1, 2016. Accessed 2017-06-17. https://www.hydro.mb.ca/regulatory_affairs/energy_rates/electricity/utility_rate_comp.shtml#analysis. See Appendix 1.

[167] Sources: Gas Alberta - http://www.gasalberta.com/gas-market/gas-rates-in-alberta, Direct Energy - http://www2.directenergy.com/direct-energy-regulations-educational/about-your-rates/your-natural-gas-rates.aspx; Enbridge Gas New Brunswick - https://naturalgasnb.com/en/for-home/customer-care/our-product-offering/#commodity-rate-history; Heritage Gas - http://www.heritagegas.com/for-home/rates/; GazMetro - http://www.grandeentreprise.gazmetro.com/prix-du-gaz/evolution-prix-du-gaz.aspx?culture=en-ca&_ga=2.147156215.1540519052.1497824223-78726804.1497824223. See Appendix 1.

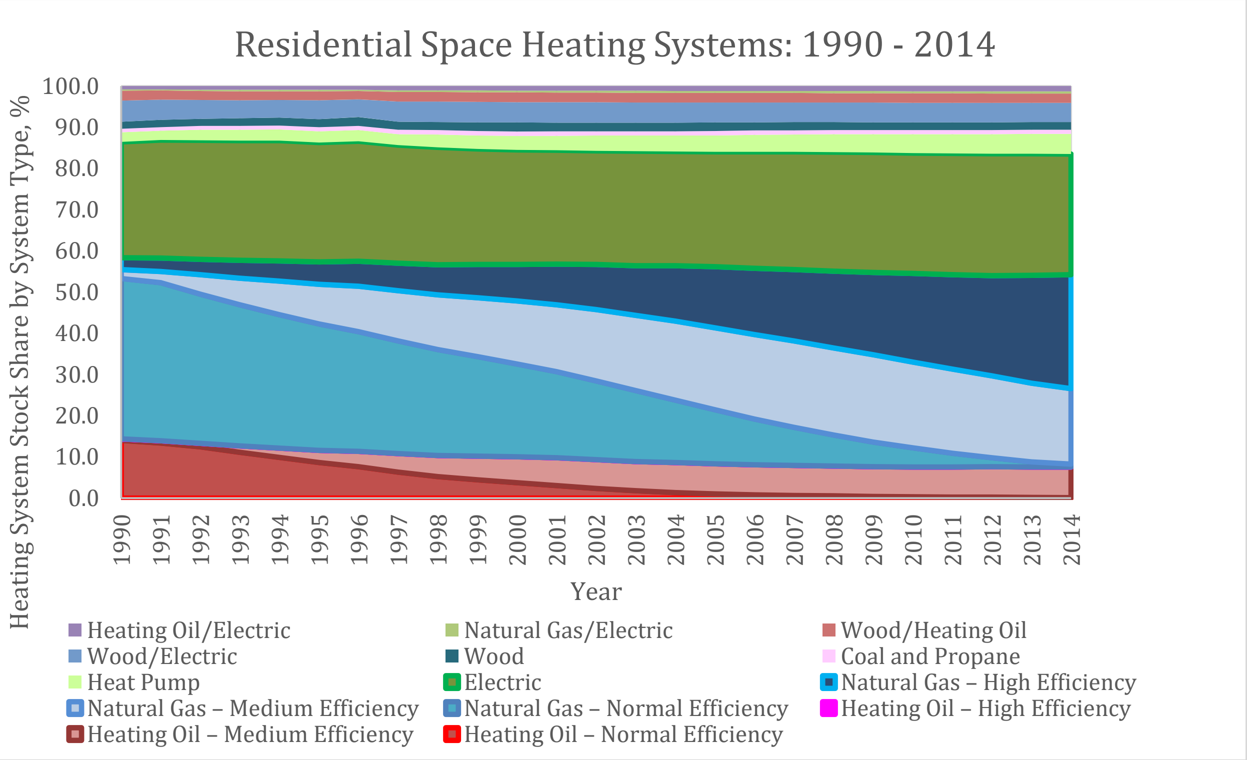
[168] Canada, Natural Resources Canada, "Heating With Oil," (2012), retrieved from http://www.housing.yk.ca/pdf/heating_with_oil_nrcan.pdf

4.2 Analysis

4.2.1 High Efficiency Furnace Replacement

Fifty-two per cent of all Canadian households have a central furnace providing heat to their home. Of these furnaces, 25% are high efficiency at this time. This change has occurred over time for both gas and oil furnaces, as shown in Figure 5.[169] Furnaces powered by heating oil gradually change over from “normal efficiency” to “medium efficiency.” Also shown in Figure 5 is natural gas furnaces, transitioning from mainly “normal efficiency” in 1990 to almost 60% of gas furnaces being “high efficiency” and 40% “medium efficiency” by 2014.

Figure 5: Residential Space Heating Systems: 1990 - 2014



Data Source: Natural Resources Canada – Energy Use Data Handbook Tables – http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

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[169] Canada, Natural Resources Canada, “Energy Use Data Handbook Tables.”

All medium and low efficiency furnaces are targeted for potential GHG reduction, based on the progress made up to 2014. First, the total household heating energy is considered. Of that, 52% is from furnaces, and 49% of those are considered medium and low efficiency, therefore targeted for improvement. Assuming an estimated 18% improvement in efficiency,[170] an energy savings is calculated. Using the previously determined GHG content of 60.1 kg/GJ (Table 13), the corresponding GHG emissions from the average home heating fuel, the estimated national GHG reduction is 3.1 Mt CO_2 e/yr (Table 15).

Table 15: Furnace Replacement Savings Estimate: Household and National

Furnace Replacement Savings Estimate For One Household:

Business As Usual Case For an Average Household:		
Average Annual Energy Use for Household, Canada (2014)	112	GJ
Energy Use for Home Heating in Average Household, %	64%	
Average Annual Energy Use for Home Heating in Average Household, GJ	**71.2**	**GJ**
Energy and GHG Savings Case:		
% of Households heated by furnaces	52%	
% that are not high efficiency - gas furnaces plus others	49%	
Expected increase in efficiency	18%	
Estimated New Energy Use per Household, GJ	**67.9**	**GJ**
Estimated Energy Savings for an Average Canadian Household:	**3.3**	**GJ**
Estimated GHG Emissions Reduction per household	**196**	**kg CO_2e/yr**

Furnace Replacement Savings - National Total:

Number of households (2016)	**15,412,443**	
BAU CO_2 Emissions per year	**66.0**	**Mt CO_2e/yr**
Energy Savings case - CO_2 emissions per year	**62.9**	**Mt CO_2e/yr**
Estimated GHG Emissions Reduction, National	**3.1**	**Mt CO_2e/yr**

Corresponding costs are estimated for the high efficiency furnace replacements. In addition, the previously noted energy prices are used to determine estimated cost savings realized

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[170] Ann Bailey, “Energy Star Most Efficient Criteria – 2017,” (2016), U.S. Environmental Protection Agency. Average of figure for clothes washers, dishwashers and refrigerators. Retrieved from www.energystar.gov/sites/default/files/10 3 16_Final ENERGY STAR_Most Efficient 2017.pdf

through lower energy use. Inflation rate is assumed at 1.7%[171] and discount rate is eight percent. Costs are summarized in Table 16.

Table 16: High Efficiency Furnace Costs: Numbers for One Household

	1. High Efficiency Furnace - capital costs:	20	years life	Energy use per year:		2. High Efficiency Furnace, op costs per year:	
		old	new	GJ-old	GJ-new	old	new
	Assumed no incremental capital costs						
TOTAL - undiscounted		**$ 0**	**$ 0**	**71.2**	**67.9**	**$ 1,362**	**$ 1,300**
Total discounted net present value[1]	**$ 676**						
Undiscounted annual benefit	**$ 66**						
Discounted annual benefit	**$ 34**						

1. Inflation rate for operating costs, electricity prices, future capital = 1.7% per year. Discount rate = 8%.

4.2.2 Energy Star (higher efficiency) Appliances Replacement

Forty-six per cent of major appliances in Canada are Energy Star certified based upon 2011 data. Current major appliance energy use is 7.8 GJ per year per household. Energy Star rates its most efficient appliances to be 23% on average better than the typical appliance.[172] In estimating potential energy savings, a 23% energy savings is applied to 54% of households. For the corresponding energy savings, the energy is sourced from electricity, which produces 34 kg CO2e/GJ in GHG emissions. The emissions savings is therefore estimated as shown in Table 17. These numbers indicate a potential emissions reduction from 0.8 Mt CO_2 per year nationally:

Table 17: Major Appliances Savings Estimate: Household and National

Major Appliance Savings Estimate For One Household:		
Business As Usual Case For an Average Household:		
Average Annual Energy Use for Household, Canada (2014)	112	GJ
Energy Use for Major Appliances in Average Household, %	7%	
Average Annual Energy Use for Appliances in Average Household, GJ	**7.8**	**GJ**

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[171] Canada, Statistics Canada,“Consumer Price Index, Historical Summary.” Accessed 2017-08-28. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm

[172] Ann Bailey, “Energy Star Most Efficient Criteria – 2017.”

Energy and GHG Savings Case:		
Estimated Energy Savings, as % of Old Appliance Energy Use	23%	
Appliances % already rated by Energy Star	46%	
Estimated New Energy Use per Household, GJ	**6.8**	**GJ**
Estimated Energy Savings for an Average Canadian Household:	**1.0**	**GJ**
Estimated GHG Emissions Reduction per household	**53**	**kg CO$_2$e/yr**
Major Appliance Savings Estimate - National Total:		
Number of households (2016)	**15,214,443**	
BAU CO2 Emissions per year	**6.5**	**Mt CO$_2$e/yr**
Energy Savings case - CO$_2$ emissions per year	**5.7**	**Mt CO$_2$e/yr**
Estimated GHG Emissions Reduction, National	**0.8**	**Mt CO$_2$e/yr**

The corresponding cost estimate is based upon energy cost savings which corresponds to the GHG emissions reduction. In the case of electricity savings, a net present value for a twenty year life is calculated, assuming the current electricity price is inflated at 1.70% annually and discounted at eight percent.

Table 18: Energy Star Appliance Costs: Numbers for One Household

	1. Energy Star Large Appliances - capital costs:	20	years life	Energy use per year:		2. Energy Star Large Appliances, op costs per yr	
		old	new	GJ-old for appliances	GJ-new	old	new
	Assumed no incremental capital costs						
TOTAL - undiscounted		**$ 0**	**$ 0**	**7.8**	**7.0**	**$ 269**	**$ 240**
Total discounted net present value[1]	**$ 308**						
Undiscounted annual benefit	**$ 30**						
Discounted annual benefit	**$ 15**						

1. Inflation rate for operating costs, electricity prices, future capital = 1,7% per year. Discount rate = 8%.

4.2.3 Household Light Bulb Replacement

The BAU case assumes the number and types of lightbulbs noted in the 2011 household survey for the average Canadian household (Table 8). In evaluating the energy savings of lightbulb replacement for all households in Canada, we assume all lightbulbs that are not yet Light Emitting Diode (LED) are changed out to LED bulbs or LED tubes in the case of fluorescent tubes, as they have the lowest energy use and offer the longest life.[173] Based upon the assumption of hours operation per year for each bulb, and the wattages noted below, average energy use for lightbulbs was calculated for an average Canadian household, for BAU and the energy savings case.

After energy use is calculated, the corresponding GHG emissions are calculated for the two cases, considering that all energy in this case is from electricity, which results in 34 kg CO_2e/GJ GHG emissions. A savings of 5.2 Mt CO_2eq/yr is estimated (Table 19).

Table 19: Lightbulb Energy Savings Estimate: Household and National

Lightbulb[1] Energy Savings Estimate For One Household:

Business As Usual Case For an Average Household:				
Average Annual Energy Use for Household, Canada (2014)			110	GJ
	No.	Hours operating per year		
Halogen bulbs	9	2000	4.9	
Compact fluorescent bulbs	10	2000	0.9	
Reg. fluorescent tubes	11	2000	2.5	
LED tubes	0	2000		
Incandescent bulbs	12	2000	5.2	
LED bulbs	0	2000	0.0	
TOTAL Energy Use per household per yr			13.5	GJ
Energy and GHG Savings Case:				
	No.	Hours operating per year		
Halogen bulbs	0	2000	0.0	
Compact fluorescent bulbs	0	2000	0.0	
Reg. fluorescent tubes	0	2000	0.0	
LED tubes	11	2000	1.5	
Incandescent bulbs	0	2000	0.0	
LED bulbs	31	2000	2.2	
TOTAL Energy Use per household per yr			3.7	GJ
Estimated Energy Savings for an Average Canadian Household:			**9.8**	**GJ**
Estimated GHG Emissions Reduction per household[2]			**337**	**kg CO_2e/yr**
Lightbulb Energy Savings Estimate - National Total:				
Number of households		15,412,443		
BAU CO_2 Emissions per year			**7.2**	**Mt CO_2e/yr**
Energy Savings case - CO2 emissions per year			**2.0**	**Mt CO_2e/yr**

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[173] "Lighting - Energy Efficiency Reference Guide," CEATI International, (2014). http://www.ceati.com/freepublications/7061_Guide_Web.pdf

Estimated GHG Emissions Reduction - National			**5.2**	**Mt CO_2e/yr**

1.Lamp assumptions: (Sources: "Lighting - Energy Efficiency Reference Guide," CEATI International, (2014). Retrieved from http://www.ceati.com/freepublications/7061_Guide_Web.pdf
Incandescent = 60 W/lamp, avg lamp life= 1000 hrs, hours op. = 2000 hrs/yr, 15.3 lumens/W
Halogen = second type of incandescent, double-ended small tube. Assumed 75 W/lamp, life = 2000 hrs, hours op. = 2000 hrs/yr, 14.7 lumens/W
Compact fluorescent = 13 W/lamp, avg lamp life 10,000 hrs, hours op. = 2000 hrs/yr, 49 lumens/W
Long fluorescent (48") = 32W/lamp, avg lamp life = 20,000 hrs, hours op. = 2000 hrs/yr, 90 lumens/W
LED bulb - screw-in base = 10 W/lamp, avg lamp life 25,000 hrs, hours op. = 2000 hrs/yr, 83 lumens/W
Long LED (48") = 19 W/lamp, life 50,000 hrs, hours op = 2000 hrs/yr, 87 lumens/W
2. 1 kWh = 0.0036 GJ, or 277.78 KWh = 1 GJ

Next, the corresponding cost savings is calculated. Based upon average electricity costs in Canada, a net present value is calculated assuming 1.70% inflation and eight percent discount rate (Table 20). When calculating net present value of capital costs, the costs are spread throughout the twenty year life as they would not all be incurred in the first year. Capital costs of the choices of bulbs were sourced from currently available commercial data.[174]

Table 20: Lightbulb Costs: Numbers for One Household

	1. Lightbulb - capital costs: Lifetime = 20 years				2. Lightbulb – op. costs per year:		
Lightbulb capital costs over 20 years:	annual hrs of use	hrs of life	old	new	old	new	Elect price, $/KWhr[1]
Halogen	2000	2000	$ 432	$ -	$ 167	$ -	0.124
Compact fluor.bulb	2000	10000	$ 50	$ -	$ 32	$ -	0.124
Reg. fluor. tube	2000	20000	$ 110	$ -	$ 87	$ -	0.124
LED - tube	2000	50000	$ -	$ 264	$ -	$ 52	0.124
Incandescent	2000	1000	$ 898	$ -	$ 179	$ -	0.124
LED bulb - none in BAU case	2000	25000	$ -	$ 87	$ -	$ 77	0.124
Undiscounted			**$ 1,490**	**$ 350**	**$ 465**	**$ 129**	
Total discounted net present value[2]	**$ 4,822**						
Undiscounted annual benefit	**$ 489**						
Discounted annual benefit	**$ 241**						

1. Source: https://www.hydro.mb.ca/regulatory_affairs/energy_rates/electricity/utility_rate_comp.shtml#analysis
2. Inflation rate for operating costs, electricity prices, future capital = 1.7% per year. Discount rate = 8%.

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[174] Prices from Canadian Tire, accessed June 16, 2017 - http://www.canadiantire.ca/en/lighting/light-bulbs.html

4.2.4 Water Heating Efficiency Installations – low flow showerhead, low flow faucets

These installations will serve to reduce hot water volumes used by the average household, and therefore reduce water heating fuel requirements and associated GHG emissions. Fifty-nine per cent of water heating needs are from showers and faucets.[175] Low-flow shower heads and faucet aerators can reduce flow by 30%.[176] Recent data also shows 90% of households with a hot water heater have at least one low-flow showerhead already. Using caution, savings are estimated for two groups: an additional 10% savings by current users of at least one low-flow showerhead, assuming they have additional efficiencies to achieve, and 30% savings for the remaining 10% of water tank owners. The energy savings of 30% is thus applied to only 10% of households, while a 10% savings is applied to the remaining 90% of households.

The energy savings from water heating has an estimated GHG emissions level of 51.8 kg/GJ (Table 14), resulting in the estimated GHG reduction presented in Table 21. Estimated national GHG reduction with these changes is 2.1 Mt/year.

Table 21: Low Flow Water Heater Savings Estimate: Household and National

Low Flow Water Heater Savings Estimate For One Household:		
Business As Usual Case For an Average Household:		
Average Annual Energy Use for Household, Canada (2014)	112	GJ
Water Heater Energy Use for Home Heating in Average Household, %	19%	
Average Annual Energy Use for Water Heater in Average Household, GJ	**21.4**	**GJ**
Energy and GHG Savings Case:		
% of Households with one lowflow showerhead already	90%	
Assumed increase in efficiency for the majority	10%	
Expected increase in efficiency for the remainder	30%	
Estimated New Energy Use per Household, GJ	**18.8**	**GJ**
Estimated Energy Savings for an Average Canadian Household:	**2.6**	**GJ**
Estimated GHG Emissions Reduction per household	**133**	**kg CO_2e/yr**
Low Flow Water Heater Savings - National Total:		
Number of households (2016)	15,412,443	
BAU CO_2 Emissions per year	**17.1**	**Mt CO_2e/yr**
Energy Savings case - CO_2 emissions per year	**15.0**	**Mt CO_2e/yr**
Estimated GHG Emissions Reduction, National	**2.1**	**Mt CO_2e/yr**

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[175] Canada, Natural Resources Canada, "Water Heater Guide," (2012). Retrieved from http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/equipment/WaterHeaterGuide_e.pdf

[176] Ibid.

Based upon the previously calculated home water heating average energy cost of $18.30/GJ, the cost savings is shown in Table 22. When calculating the net present value, capital costs are expended in the first year.

Table 22: Low Flow Plumbing Fixture Costs: Numbers for One Household

	1. Low flow fixtures - capital costs:		20 years life		Energy use per year		2. Low flow fixtures, op costs per yr:	
	No. per house	Hrs of life	old	new	GJ-old for water heating	GJ-new	old	new
Low flow faucet aerator	2	43,800	$ -	$ 79.92				
Low flow shower head	1	43,800	$ 99.96	$ 99.96				
TOTAL - undiscounted			**$ 99.96**	**$ 179.88**	**21.4**	**18.8**	**$ 392**	**$ 345**
Est. cost – aerator[1]	$ 9.99							
Est. cost - shower head[1]	$ 24.99							
Regular shower head[1]	$ 24.99							
Total discounted net present value[2]	**$ 429**							
Undiscounted annual benefit	**$ 45**							
Discounted annual benefit	**$ 21**							

1. Prices from Canadian Tire - http://www.canadiantire.ca/en/lighting/light-bulbs.html, accessed 2017-06-16
2. Inflation rate for operating costs, electricity prices, future capital = 1.7% per year. Discount rate = 8%.

4.2.5 Programmable thermostat installation

As a last modest improvement in all households in Canada, smart thermostats are considered, programmed to reduce the temperature automatically at night and therefore save heating fuel consistently, and reduce corresponding GHG emissions. Thirty-seven per cent of households in Canada currently have programmable thermostats already; we assume the remainder will make the change.[177] Energy savings in the order of 9 or 10% may be realized if a programmable thermostat is used correctly.[178] An energy savings of 10% is applied to 63% of

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[177] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

[178] "Programmable Thermostats," Energy Star, accessed 2017-07-19. https://www.energystar.gov/products/heating_cooling/programmable_thermostats; "Thermostats – Energy Saver," U.S. Department of Energy, accessed 2017-07-19. https://energy.gov/energysaver/thermostats

households' home heating energy requirements, and the corresponding GHG emissions are calculated assuming 60.1 kg CO2e/GJ is saved (Table 13). National GHG emissions reductions through energy savings are estimated to be 4.2 Mt CO$_2$e/year:

Table 23: Programmable Thermstat Energy Savings Estimate: Household and National

Programmable Thermostat Energy Savings Estimate For One Household:		
Business As Usual Case For an Average Household:		
Average Annual Energy Use for Household, Canada (2014)	112	GJ
Energy Use for Home Heating in Average Household, %	64%	
Energy Use for Home Heating in Average Household, GJ	71.2	GJ
Energy and GHG Savings Case:		
Estimated Energy Savings, for New Installations	10%	
Households % already using Programmable Thermostat	37%	
Estimated New Energy Use Energy Savings	66.7	GJ
Estimated Energy Savings for an Average Canadian Household:	**4.5**	**GJ**
Estimated GHG Emissions Reduction per household	**270**	**kg CO$_2$eq/yr**
Programmable Thermostat Energy Savings - National Total:		
Number of households (2016)	15,214,443	
BAU CO$_2$ Emissions per year	**66.0**	**Mt CO$_2$e/yr**
Energy Savings case - CO$_2$ emissions per year	**61.8**	**Mt CO$_2$e/yr**
Estimated GHG Emissions Reduction - National	**4.2**	**Mt CO$_2$e/yr**

The corresponding cost savings is estimated by considering the energy cost savings corresponding to the home heating savings shown above. As noted earlier, home heating average costs in Canada are estimated at $19.13/GJ. When calculating the net present value of capital costs, all capital is expended in the first year.

Table 24: Programmable Thermostat Costs: Numbers for One Household

	1. Programmable Thermostat - capital costs:	20	years life	Energy use per year		2. Programmable Thermostat, op costs per yr:	
		old	new	GJ-old for heating	GJ-new	old	new
Programmable thermostat[1]		$ -	$ 3.36				
TOTAL - undiscounted		**$ -**	**$ 3.36**	**71.2**	**66.7**	**$ 1,362**	**$ 1,276**
Total Discounted Net present value[2]	**$ 927**						
Undiscounted annual benefit	**$ 90**						
Discounted annual benefit	**$ 46**						

1.Prices from Canadian Tire - http://www.canadiantire.ca/en/lighting/light-bulbs.html, accessed 2017-06-17. Capital cost of $33.59 is only applied to 10% of households, as 90% already have one

2. Inflation rate for operating costs, electricity prices, future capital = 1.7% per year. Discount rate = 8%.

4.2.6 Summary of Residential GHG Emissions Savings

Below is a summary of the GHG emissions savings calculations for all categories and the combined total, for all households in Canada. GHG savings is estimated at 15.2 Mt per year or 10% from all households in Canada changing to high efficiency furnaces, all Energy Star major appliances, all LED lightbulbs, all having low flow aerators and showerheads, and all using smart thermostats.

Table 25: Estimated Energy Savings and GHG Reductions from Home Retrofits in Canada

Business As Usual (BAU):	Average Canadian Home as per Statistics Canada. See below.	
GHG Emission Reduction Case:	Furnaces are changed out to high efficiency if not already done. All lightbulbs are changed to equivalent LED if they are not already. Appliances are changed to above average Energy Star rating. Lowflow devices and smart thermostats implemented in homes that do not already have them.	
Number of Households (2016)	15,412,443	
Item	**Business As Usual (BAU)**	**GHG Emission Reduction Case**
	Annual GHG emissions, Mt/year	Annual GHG emissions, Mt/year
1. Furnaces		
Install high efficiency furnace in all households	66.0	62.9
2. Appliances		
Refrigerator, freezer, dishwasher, washer, dryer	6.6	5.7
3. Lightbulbs		
Change out all incandescent, halogen and compact fluorescent to LED	7.2	2.0
4. Low Flow appliances, hot water heater savings		
Low-flow faucet aerators, low-flow shower heads	17.1	15.0
5. Smart programmable thermostats	(already counted in 1.)	-4.2
TOTAL	**96.8**	**81.6**
GHG Reduction, Mt/year		**15.2**

The costs for all projects are summarized below and an abatement cost is calculated (Table 26). Abatement costs, capital, are -\$2/tonne CO_2e emissions while abatement costs, operating, are -\$335/tonne CO_2e.

Table 26: Estimated Costs of GHG Reductions from Home Retrofits in Canada

Business As Usual (BAU):	Average Canadian Home as per Statistics Canada. See below.	
GHG Emission Reduction Case:	All lightbulbs are changed to equivalent LED if they are not already. Appliances are changed to above average Energy Star rating and plumbing changes and smart thermostat implemented in homes that do not already have them.	
Number of Households	15,412,443	
Assumed life cycle	20 years	20 years
Item	**Business As Usual (BAU)**	**GHG Emission Reduction Case**
Capital Costs Averaged Per Year[1]		
1. Furnace replacement	Assumed no change in costs, just changed out furnaces over 20 years	
2. Appliance costs	Assumed no change in costs, just changed out appliances over 20 years	
3. Lightbulb retrofit	$ 687,644,697	$ 161,736,839
4. Low flow water fixtures, affecting water heater energy use	$ 77,031,390	$ 138,619,512
5. Programmable thermostat	$ -	$ 2,588,520
TOTAL	$ 764,676,087	$ 302,944,872
Estimated Capital Cost Savings per year		**-$ 461,731,215**
Est. Capital Cost Savings per year per household		**-$ 30**
	Business As Usual (BAU)	**GHG Emission Reduction Case**
Operating Costs Averaged Per Year[1]		
1. Furnace replacement	$ 11,355,796,361	$ 10,834,971,289
2. Appliance costs	$ 2,239,732,829	$ 1,961,550,354
3. Lightbulb retrofit	$ 4,408,980,791	$ 1,219,105,504
4. Low flow water fixtures	$ 3,265,517,968	$ 2,873,648,413
5. Programmable thermostat	$11,355,796,361	$ 10,639,172,902
TOTAL	**$ 32,625,824,310**	**$ 27,528,448,463**
Estimated Operating Cost Savings per year		**-$ 5,097,375,846**
Est. Cost Savings per year per household, opex		**-$ 331**
CO2eq Mt/yr	96.8	81.6
CO2eq Reduction, Mt/yr		15.2
Abatement Costs, Capital - $/t CO_{2e}		**-$2**
Abatement Costs, opex - $/t CO_{2e}		**-$335**

1. Note: All costs are Net Present Values discounted at 8% over 20 year project life. Fuel and power costs are inflated from 2017 at 1.7% per year.

The numbers indicate if all abatement activities are performed throughout all households in Canada, over a twenty-year lifespan capital cost savings are estimated at $462 million per year while operating expenses are reduced by $5.1 billion per year (discounted). Average savings per household per year are estimated at $30/year in capital costs and $330/year (discounted) in operating costs.

All projects achieve substantial energy use savings and therefore GHG emissions reductions. The analysis demonstrates the lightbulb retrofit project will save Canadians $526 million per year in capital costs of bulbs over a twenty-year estimated life. The higher initial cost of LED bulbs is offset significantly by their much longer estimated life, reducing overall costs to consumers. Low flow plumbing fixtures and programmable thermostats are a small incremental cost since we assume these items would not otherwise be purchased.

The abatement costs are negative, indicating an overall benefit in both capital and operating costs over the life of the projects. 15.2 Mt/yr in GHG emissions reduction represents 2% of Canada's total annual emissions, or 10% of Canada's annual residential 2015 GHG emissions.

The consumer also benefits through avoided carbon tax payments, depending on which region of Canada they reside in. Assuming the federal government levels of backstop carbon tax announced in 2017, annual carbon tax savings are estimated at $307 million nationally, or $20 per year per household.

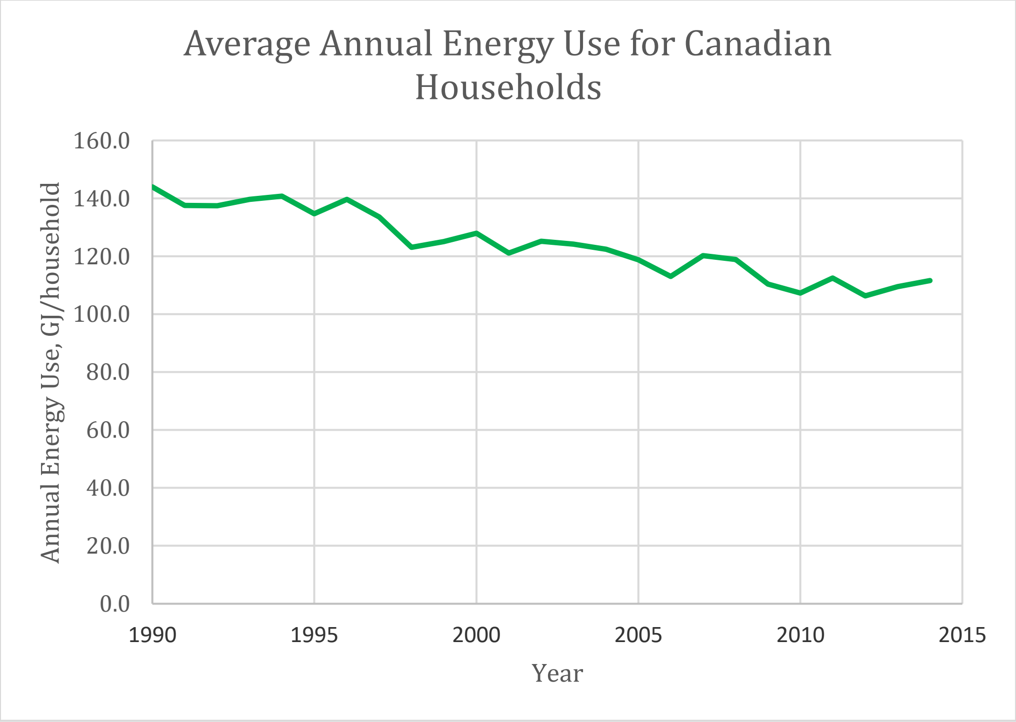
4.3 Policy Recommendations

Given the implementation of Canada's national carbon tax backstop, market pressures will drive consumers to reduce their residential fuel usage. Energy efficiency policies such as those reviewed here complement a carbon tax through providing consumers with a nudge toward short-term methods of fuel and therefore cost reduction. Longer term methods of fuel reduction would include buying a smaller house or implementing larger scale renewable energy technology with larger scale investment.

Various provinces have implemented energy efficiency incentive programs in recent years, targeting GHG emissions reductions.[179] All programs appeal to Canadians through the consideration of financial incentives. The analysis above indicates these methods of GHG reduction have a financially positive impact for homeowners in both overall capital costs and operating costs. The average capital costs per household are reduced compared to the BAU case by $30/year over twenty years. The average operating costs (fuel used) per household are reduced compared to the BAU case by $331/year over twenty years.

Data indicates reasonable uptake over the years with high efficiency furnaces, programmable thermostats and newer, low energy lightbulbs.[180] Average household energy use has decreased 22.5% from 1990 to 2014 (Figure 6).[181]

Figure 6: Average Annual Energy Use for Canadian Households



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[179] "Find energy rebates in your province," Canadian Home Workshop, accessed 2017-08-21, http://canadianhomeworkshop.com/651/home-renovations/find-energy-rebates-in-your-province

[180] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

[181] Ibid.

Source: Canada, Natural Resources Canada, “Energy Use Data Handbook Tables,” http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

One wonders whether there is a need for a new policy in this area as consumers are gradually changing over to lower energy choices in these areas. Energy used per household is declining, however, total household energy use in Canada has increased 9.5% over the same time period.[182] Consumer demand has resulted in pushing up Canada’s total residential energy demand due to increases in population, but also due to increases in a few key areas: an increasing average home size, and increased demand in appliances in the home such as televisions, computers, game consoles, and other popular products. In the past, consumers have demonstrated uptake of certain specific products that were targeted with incentive programs, rather than general knowledge and change in underlying choices regarding energy consumption. This points to the need for a specific policy.

I recommend additional consumer-based social marketing strategies, in order to focus on local, specific barriers, and address and remove them.[183] Additional policies could include incentive programs regarding additional classes of appliances, but more importantly education reaching out further into the community at a local level, and post-appraisal of any policy instruments implemented.[184]

A policy of an overall audit program is also recommended, with more education focus than previous programs. In addition, regulation gradually imposed over time may be required to meet the larger reduction targets named in the Paris agreement.

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[182] Ibid.

[183] Dahlia Streimikiene, “Assessment of reasonably achievable GHG emission reduction target in Lithuanian households,” *Renewable and Sustainable Energy Reviews*, (2015), Vol.52, pp.460-467. http://linkinghub.elsevier.com/retrieve/pii/S1364032115007583

[184] Ibid.

Pros

Energy efficiency programs have already been successful in Canada for many years, and these suggested policies will continue that trend. From 1990 to 2014, GHG emissions per household from major appliances fell 61%, and GHG emissions per household from lighting and appliances in general fell 43%. Emissions per household from home heating fell 33% in the same period.[185] These figures indicate households are actively taking part in reducing GHG emissions.

However, GHG emissions per household for appliances other than "major" appliances (stove, fridge, washer, dryer, dishwasher, freezer) increased by 52% from 1990 to 2014.[186] For that same period, the average household area also increased by 17%, partially offsetting some of the home heating efficiency gains seen.[187] The growing category of other appliances includes televisions, computers, game consoles and tablets, among other things.

The areas of new appliance categories and home size have barriers for consumers to overcome, including lack of information. By developing policies that specifically address additional appliance categories, home size, and a broader GHG education program in general, emissions in these areas will be reduced.

Cons

Reasons why retrofit programs are not taken up by the public include concerns about financial arrangements if capital up front is large, and skepticism that the scheme will actually generate the savings it claims.[188] Other reasons for poor rates of implementation include lack of access to capital and split incentives between landlords and tenants.[189] When funds are freed up

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[185] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

[186] Ibid.

[187] Ibid.

[188] P. Webber, A. Gouldson, N. Kerr, "The impacts of household retrofit and domestic energy efficiency schemes: A large scale, ex post evaluation," *Energy Policy*, (2015), Vol. 84, pp. 35-43. http://www.sciencedirect.com.ezproxy.lib.ucalgary.ca/science/article/pii/S0301421515001706

[189] Ibid.

because energy costs decrease due to energy efficiency measures, a rebound of increased use of energy may also occur.[190]

Another major barrier to implementation of methods of GHG reduction and energy efficiency by consumers is basic lack of information regarding GHG emissions and the reasoning behind abatement measures, in addition to information regarding technological recommendations.[191]

Political and Social Feasibility

Canadian consumers have slowly moved into the better energy efficiency products considered here, over the last twenty-five years. The combination of various incentive programs, information programs, and general presence in the market have been successful in lowering GHG emissions to some degree and the abatement methods discussed here are accepted as mainstream products in the market. As noted above however, certain consumer behaviors contradict the GHG emissions reduction focus, displaying average Canadian choices in a few key areas. In addition, barriers to full implementation still exist.

5.0 Commercial and Institutional Retrofits: Offices, Malls, Hospitals and Schools

5.1 Assumptions

The allocation of energy use for commercial and institutional needs in Canada is shown in Table 27.[192]

Table 27: Energy Use by Activity Type - Commercial and Institutional Buildings in Canada - 2014

	PJ	Percentage
Offices	351	36
Retail Trade	161	17
Educational Services	126	13
Health Care and Social Assistance	107	11

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[190] Ibid.
[191] Dahlia Streimikiene, “Assessment of reasonably achievable GHG emission.”
[192] Canada, Natural Resources Canada, “Energy Use Data Handbook Tables.”

Accommodation and Food Services	74	8
Wholesale Trade	56	6
Transportation and Warehousing	38	4
Arts, Entertainment and Recreation	25	3
Information and Cultural Industries	21	2
Other Services	16	2
TOTAL	983	100

Source: Natural Resources Canada - Energy Use Data Handbook Tables - http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm

Total energy use for commercial and institutional buildings in Canada was 983 PJ in 2014, and includes 754.7 million square metres (m^2).[193] Of the total energy use for commercial and institutional buildings above, 11% is used for lighting, and 56% is used for heating, two of the largest categories of energy use.[194] The corresponding GHG emissions from that energy use is 4.5 Mt CO_2e/yr for lighting and 27.9 Mt CO_2e/yr for heating.[195] This section considers how the energy needs for lighting and heating of commercial and institutional space in Canada may be reduced through known technology and minor retrofits.

For the BAU case, the 2014 level of GHG emissions from heating and lighting energy use in the commercial and institutional sector is assumed constant over a twenty-year project life.

Little detailed data is available regarding equipment currently or historically utilized in commercial and institutional applications, beyond the Survey of Commercial and Institutional Energy Use report and the Energy Use Data Handbook Tables referenced here.[196] Data also shows 37% of all floor space in commercial and institutional buildings in Canada underwent some energy efficiency renovations in the five years from 2005 through 2009.[197] Energy use is constant from 2000 to 2014, as is GHG emissions for all commercial and institutional buildings

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[193] Ibid.

[194] Canada, Natural Resources Canada, “Survey of Commercial and Institutional Energy Use – Buildings 2009 – Detailed Statistical Report,” Ottawa (2012), p. 15. Retrieved from http://oee.nrcan.gc.ca/publications/statistics/scieu/2009/pdf/scieu2009.pdf

[195] Ibid.

[196] Ibid, p. 15.

[197] Ibid.

in Canada.[198] However a trend of declining energy use per square metre, or "energy intensity," is seen from 2004 to 2014.[199]

Subramanyam et al develop a reference scenario for Alberta incorporating falling energy intensities with time due to improved technology penetration levels.[200] Subramanyam et al estimate an energy intensity reduction in building heating and lighting areas ranging from 10% up to 50% to 2050.[201] It is therefore realistic to assume a decline in energy use through continued penetration of the market by existing technology including high efficiency furnaces and high efficiency light fixtures.

From 2004 to 2014, the average decrease in energy intensity in the commercial and institutional sector was 1.7% per year.[202] Assuming this trend continues for ten more years, this paper assumes a 17% reduction on average in current energy use for lighting and building heating, and a corresponding reduction in GHG emissions and operating costs.

Capital costs are not estimated due to the lack of data regarding current inventory. This imposes an unknown potential barrier to implementation of these measures. While a decrease in energy use will always result in an annual energy cost savings and therefore negative abatement cost, if the corresponding related capital is significant compared to the BAU case, there may be financial barriers to change. Nonetheless, historically there is evidence of slow but gradual implementation of higher efficiency equipment in these two areas, indicating within the assumptions of known technology currently in the market, incremental capital costs can be manageable.

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[198] Ibid.

[199] Ibid.

[200] V. Subramanyam, M. Ahiduzzaman, A. Kumar, "Greenhouse gas emissions mitigation potential in the commercial and institutional sector," *Energy and Buildings*, (2017), Vol. 140, pp.295-304. http://www.sciencedirect.com.ezproxy.lib.ucalgary.ca/science/article/pii/S0378778817304188

[201] Ibid.

[202] Canada, Natural Resources Canada, "Energy Use Data Handbook Tables."

When determining GHG emissions levels and a potential achievable reduction, the source of energy for electricity, in the case of lighting, and a mix of sources for heating, are considered. As noted earlier, average GHG emissions for electricity in Canada are estimated at 34.4 kg/GJ. Any energy savings in lighting are assumed fueled 100% by electricity. The energy source composition for heating of commercial and institutional buildings in Canada is found in Table 28.[203] Applying the GHG emissions levels to each source by percentage, the average total GHG emissions for heating of commercial and institutional buildings is calculated.

Table 28: Commercial and Institutional Heating Energy Source Composition

	% Of Heating Energy Source for All Canada Commercial/Institutional Buildings	**GHG Emissions - kg/GJ**
Electricity	24.2%	34.4
Natural Gas	60.1%	56.1
Light Fuel Oil and Kerosene	6.9%	77.4
Heavy Fuel Oil	2%	77.4
Other	7%	86.5
TOTAL	100%	54.9

Source: Natural Resources Canada, http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/scieu/2009/tables.cfm

The cost of energy for commercial and institutional buildings is used to determine potential associated cost savings. Average cost for commercial electricity in Canada is estimated at $0.113 per kWh from April, 2016 data.[204] Natural gas price is estimated at $12.53/GJ from May, 2016 data,[205] and fuel oil price is estimated at $17.23/GJ from June, 2017 data.[206]

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[203] Canada, Natural Resources Canada, “Survey of Commercial and Institutional Energy Use.”

[204] Hydro Quebec,“Comparison of Electricity Prices in Major North American Cities” (2016). http://www.hydroquebec.com/publications/en/docs/comparaison-electricity-prices/comp_2016_en.pdf. See Appendix 1.

[205] Sources: Gas Alberta - http://www.gasalberta.com/gas-market/gas-rates-in-alberta, Direct Energy - http://www2.directenergy.com/direct-energy-regulations-educational/about-your-rates/your-natural-gas-rates.aspx; Enbridge Gas New Brunswick - https://naturalgasnb.com/en/for-home/customer-care/our-product-offering/#commodity-rate-history; Heritage Gas - http://www.heritagegas.com/for-home/rates/; GazMetro - http://www.grandeentreprise.gazmetro.com/prix-du-gaz/evolution-prix-du-gaz.aspx?culture=en-ca&_ga=2.147156215.1540519052.1497824223-78726804.1497824223. See Appendix 1.

[206] Source: Canada, Natural Resources Canada, "Heating With Oil," (2012), retrieved from http://www.housing.yk.ca/pdf/heating_with_oil_nrcan.pdf

Future operating costs for BAU and a decreased energy use case are estimated by determining an energy price per GJ. 1 GJ equals 277.78 kWh, and we apply fuel oil price to all oil and “other” categories above, the following prices are calculated:

- Average lighting energy price (100% electricity) = $31.41/GJ
- Average heating energy price (mix above) = $17.89/GJ

In calculating future operating costs as net present value, a twenty-year life is considered, with 1.7% inflation rate and eight percent discount rate.

5.2 Analysis

The BAU case assumes constant energy use for twenty years of 554 PJ/year for heating and 109 PJ/year for lighting needs, assuming flat performance from 2014. Corresponding CO_2e emissions are 34.2 Mt CO_2e/yr.

With a 17% reduction in energy needs for these two areas, the corresponding GHG emissions are reduced by 5.8 Mt CO_2e/yr. The corresponding fuel savings are found in Table 29.

Table 29: Estimated Energy Savings and GHG Reduction from Commercial and Institutional Heating and Lighting Retrofits in Canada

Business As Usual (BAU):	Energy usage for commercial and institutional buildings, 2014. Source = http://oee.rncan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=com&juris=ca&rn=37&page=0	
GHG Emission Reduction Case:	Assumed 17% reduction in energy use through replacement of light fixtures, light management programs and mechanisms, and replacement of some furnaces, heating systems, and heating control systems.	
Number of square metres, millions (2014)	754.7	
Item	**Business As Usual (BAU)**	**GHG Emission Reduction Case**
1. Capital costs	-	-
2. Operating costs		
Energy utilized for heating, PJ[1]	554	460
Energy Savings, PJ per year		94
Energy use for heating per area, GJ/m^2	0.73	0.61
Annual Operating Costs, $	$9,915,624,891	$8,229,968,660
Annual Operating Cost Savings, heating $		-$1,685,656,232
Energy utilized for lighting, PJ[1]	109	90
Energy Savings, PJ per year		18
Energy use for light per area, GJ/m2	0.14	0.12

Annual Operating Costs, $	$3,411,123,122	$2,831,232,191
Annual Operating Cost Savings, lighting $		-$579,890,931
Annual Operating Cost Savings, $ discounted[2]		-$1,113,817,057
CO2eq Mt/yr	34.3	28.5
CO2eq Reduction, Mt/yr		5.8
Abatement Costs, Capital - $/t CO_2e		**$ -**
Abatement Costs, opex - $/t CO_2e		**-$ 191**

1. Source: Natural Resources Canada - Energy Use Data Handbook Tables - http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm
2. 8% discount rate, costs inflated at 1.7% per year (average inflation rate from 2010 to 2016), 20 year life

The building owner or tenant also benefits through avoided carbon tax payments, depending on which region of Canada they reside in. Assuming the federal government levels of backstop carbon tax announced in 2017, annual carbon tax savings are estimated at $125 million nationally.

5.3 Policy Recommendations

Historical overall decreases in energy intensity and flat GHG emissions with a growing economy demonstrates the general success of the existing programs and incentives. Commercial building owners and tenants wish to lower operating costs and operate more efficiently if possible. A number of groups in Canada, government and private, have organized to efficiently list and aid in access of energy efficiency incentives and programs for commercial uses, with the goal of increasing energy sales through attracting new customers and enhancing the relationship with existing ones.[207]

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[207] PWC, “Going Green Tables- Select Federal and Provincial Incentives,” (2010). https://www.pwc.com/ca/en/sustainability/publications/going-green-tables-en.pdf ; I. Hollet & Sons Inc., “Canadian Energy Efficiency Program Study,” Government of Newfoundland and Labrador, (2011). http://www.exec.gov.nl.ca/exec/occ/publications/canadian_energy_efficiency_programs_final_report.pdf

However, GHG emissions remain flat, and in order to meet the Paris agreement targets, all areas must see a major reduction in emissions. More direct policy targeting commercial and institutional buildings can move the emissions figures downward.

The carbon tax will serve to add economic incentives to implement more efficient means to heat and light buildings. Comparing a potential savings of $125 million per year in carbon tax versus a savings in fuel costs of $1.1 billion per year however, the main driver will be fuel cost savings.

Policies that are market driven and leave choices to building owners and operators are recommended, such as an increased carbon tax, attractive finance options for required capital, or tax incentives or rebates for implementing high efficiency heating and light systems. Some low cost mandatory policies that could improve energy efficiency practices in commercial buildings include informative billing/real time usage feedback, combined with mandatory energy audits and reporting.[208] Real-time feedback has resulted in reported savings of up to 15%.[209] While a mandatory energy audit and reporting requirement will not require building owners to retrofit or implement changes to reduce energy usage, it aids in benchmarking current energy use and promote awareness of existing and new efficiency measures that could be implemented. These practices represent the first step toward an awareness of actual energy usage and the building of a knowledge base regarding current efficiency.

Pros

The current programs are resulting in improved energy efficiency, however they could be more effective with full sector uptake. Gathering actual data and evaluating the post occupancy

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[208] E. Mohareb, J. Row, "Improving Energy Efficiency In Alberta's Buildings: Best Practices, Key Actors and the Role of Sustainable Energy Organizations," The Pembina Institute, (2014). https://www.pembina.org/reports/improving-energy-efficiency-in-alberta-buildings.pdf

[209] Ibid.

performance of an older building can aid in development of a detailed energy reduction plan.[210] Mandatory audit and energy data submission raises awareness and may be used to direct spending at the projects with biggest impact. Sunikka-Blank and Galvin show the most effective retrofit work begins with actual, measured energy consumption data.[211]

Cons

One of the major challenges commercial building owners deal with is the split incentive, in which the owner funds energy efficient modifications but the tenant reaps the benefits through lower utility bills.[212] Alternatively, the tenant also may have little reason to enforce energy efficient behaviour if she does not directly pay utility bills. These issues can be managed through an "energy-aligned clause"[213] that allows for cost recovery by the landlord through increased rental rates, but limiting the increase to cover the actual expenses.

Similar to the issue of tenants and lack of alignment with energy efficiency goals, for institutions, workers may not be incentivized to change behaviours in order to reduce energy use. Economic challenges include the relatively low cost of natural gas currently seen.[214] This leads to less economic incentive to reduce fuel costs, and results in longer payout times for any upfront capital investments.

The lack of data and post-appraisals can damage any effort to change energy usage.[215]

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[210] Richard Atkins and Rohinton Emmanuel, "Could refurbishment of "traditional" buildings reduce carbon emissions?" *Built Environment Project and Asset Management*, Glasgow, (2014). https://search-proquest-com.ezproxy.lib.ucalgary.ca/docview/1650538980/fulltextPDF/FC237FA1BDD748E8PQ/1?accountid=9838

[211] M. Sunikka-Blank, R. Galvin, "Introducing the prebound effect: the gap between performance and actual energy consumption," *Building Research & Information*, Vol. 40, Issue 3, pp. 260-273, (2012). http://www.tandfonline.com/doi/abs/10.1080/09613218.2012.690952

[212] Ibid.

[213] Ibid.

[214] E. Mohareb, J. Row, "Improving Energy Efficiency In Alberta's Buildings."

[215] Chung-Ming Liu, Ming-Lone Liou, Shin-Cheng Yeh, Neng-Chou Shang, "Target-aimed versus wishful-thinking in designing efficient GHG reduction strategies for a metropolitan city: Taipei," *Energy Policy*, (2009). Vol. 37. Issue 2. pp.400-406. http://linkinghub.elsevier.com/retrieve/pii/S030142150800517X

6.0 Conclusions

6.1 Summary of Key Metrics

Table 30 contains a summary of the key metrics considered for each abatement method studied.

Table 30: Summary of Key Metrics

	1. Vehicles		2. Natural Gas Industry and CCS Retrofit				
Area	**Passenger vehicles**	**Medium and heavy duty vehicles**	**Current sour gas plants**	**All Sweet gas plants**	**3. Residential retrofits**	**4. Commercial and institutional retrofits**	**TOTAL**
BAU GHG Emissions. Mt/yr	69	77	1.6	2.5	97	34	**281**
Reduced GHG Emissions, Mt/yr	37	65	0.1	0.2	82	28	**213**
GHG Reduction, Mt/yr	31	11	1.5	2.3	15	6	**68**
Capital Intensity of abatement measure, $/t	$ -	$ 39	$ 25	$ 38	-$ 2	$ -	**$ 33**
Abatement Cost, opex $/t	-$ 286	-$ 345	$ 52	$ 77	-$ 334	-$ 191	**-$ 279**
Social Cost of Carbon, Central Tendency, $/t	$ 44.23	$ 44.23	$ 44.23	$ 44.23	$ 44.23	$ 44.23	
Social Cost of Carbon, 95th Percentile, $/t	$ 181.96	$ 181.96	$ 181.96	$ 181.96	$ 181.96	$ 181.96	
Annual Incremental Capital Cost,[1] $ millions/yr	$ -	$ 2,549	$ 37	$ 88	-$ 462	$ -	**$ 2,212**
Annual Incremental Op Cost,[1] $ millions/yr	-$ 9,016	-$ 3,903	$ 75	$ 181	-$ 5,056	-$ 1,114	**-$ 18,833**
Carbon Tax[2] Payments Avoided, $millions/yr	-$ 637	-$ 285	-$ 29	-$ 47	-$ 307	-$ 125	**-$ 1,431**

1. Net present value over life of project, 1.7% inflation and 8% discount rate
2. Assumed the federal government backstop carbon tax levels: $10/t – 2018, $20/t – 2019, $30/t – 2020, $40/t – 2021, $50/t - 2022

In addition to the national figures noted above, Table 31 contains a summary including a single average passenger vehicle and a single household with the residential retrofits and passenger car replacement abatement methods from above.

Table 31: Summary of Metrics for a Single Household

Area	**Passenger Car**	**Furnace**	**Major Appliances**	**Lights**	**Hot Water Heating (low flow plumbing fixtures)**	**Programmable Thermostat**	**Total Residential Retrofit**	**TOTAL**
BAU GHG Emissions, kg/yr	3325	4280	426	465	1109	4280	10560	13886
Reduced GHG Emissions, kg/year	1807	4084	381	129	976	4011	9580	11387
GHG Reduction, kg/year	-1518	-196	-45	-336	-133	-270	-980	-2499
Capital Intensity of abatement measure, $/t	$ -	$ -	$ -	-$ 57	$ 4	$ 1		
Abatement Cost, opex $/t	-$ 286	-$ 318	-$ 342	-$ 717	-$ 353	$ 318		
Annual Incremental Capital Cost , $/yr**	$ -	$ -	$ -	-$ 57	$ -	$ -	-$ 57	-$ 57
Annual Incremental Op Cost, $/yr**	-$ 810	-$ 62	-$ 15	-$ 241	-$ 21	$ 46	-$ 294	-$ 1,104
Carbon Tax* Payments Avoided, $/yr	-$ 46	-$ 6	-$ 1	-$ 10	-$ 4	-$ 8	-$ 29	-$ 75
Notes	1. Net present value over life of project, 1.7% inflation and 8% discount rate 2. Assumed the federal government backstop carbon tax levels: $10/t – 2018, $20/t – 2019, $30/t – 2020, $40/t – 2021, $50/t - 2022							

In 2015, GHG emissions were 722 Mt CO_2e/yr. With known technology in the four areas noted above, an estimated reduction of 68 Mt CO_2e/yr or a 9% reduction may be achievable. Most of the proposed methods have negative abatement costs, in that there are significant fuel cost savings due to fuel use reductions with efficiency improvements. Associated fuel cost savings due to these energy cost savings is estimated at $18 billion per year discounted at 8% over the life of the projects. Assuming the backstop federal carbon price is applied, avoided carbon tax payments total approximately $1.4 billion per year. Two-thirds of this value is comprised of savings from passenger vehicles and residential retrofits.

The abatement cost for the various measures range from $-191/t to -$334/t, not including the gas plant projects as fuel efficiencies result in savings. These figures are of similar magnitude to the social cost of carbon. They are significantly higher in magnitude than the carbon tax range of $10 through $50/t and have more power to incentivize consumers. On a per household basis, the cost savings incentive is almost 15 times greater than the potential carbon tax savings.

In the cases of the gas plant CCS projects, there is both an incremental upfront capital expenditure and an ongoing incremental operating cost, indicating a strong regulated incentive would be required to encourage plant owners to proceed. Note the capital abatement cost is $13/t and the operating abatement cost is $33/t for the CCS application on existing sour gas plants. The range is close to that of the carbon tax.

In the case of the freight vehicles replacement to natural gas, the abatement cost savings is significant due to both higher fuel efficiency and cleaner burning natural gas compared to diesel. However, the capital costs up front are incrementally approximately $58,000 per vehicle for heavy trucks, representing a large premium over diesel vehicles and a key barrier to moving further into CNG freight vehicles.

6.2 Policy Discussion

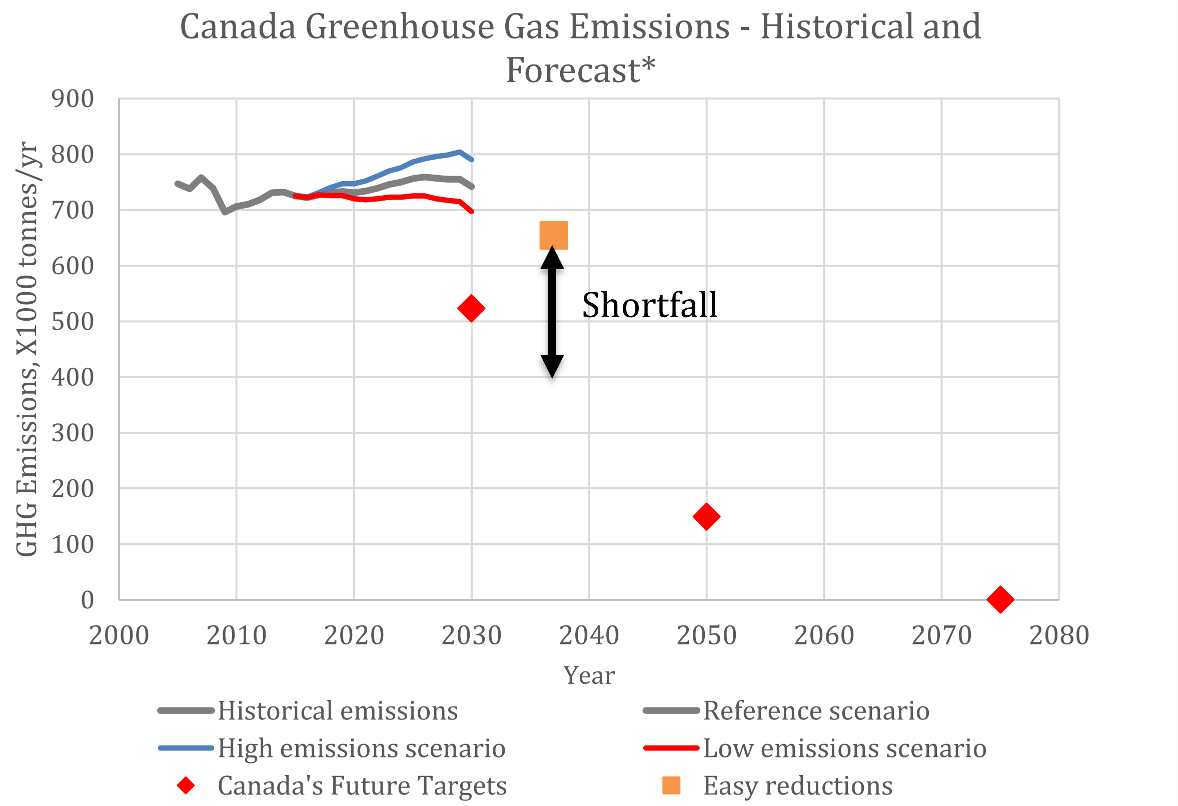
This study asks the question what magnitude decrease in GHG emissions may be achieved through common, known technology that is in the market today, and at what cost. Complementary policies to nudge Canadians toward these behaviours are summarized below:

- Passenger vehicles: New, more stringent mandatory fuel efficiency regulations based upon “best-in-class” fuel efficiencies seen globally rather than just North American markets
- Freight vehicles: A regulated changeover of the entire fleet to CNG, with potential incentives to de-risk some of the upfront costs, allocation of funds for related infrastructure, and provision of some certainty of the current federal fuel tax exemption on natural gas as a transport fuel
- Gas processing plants: Because of the significant up-front capital costs, the focus of these costs on a small stakeholder group, and the fact that a number of other measures listed here have much more beneficial abatement costs (benefits), it is not recommended these abatement projects be pursued by government
- Residential retrofits: Recommended policies include incentive programs regarding additional classes of appliances, an overall audit program with more education focus, and post-appraisal of any policy instruments implemented
- Commercial/Institutional heating and lighting retrofits: Recommended policies include an increased carbon tax, attractive finance options for required capital, tax incentives or rebates for implementing high efficiency heating and light systems; in addition, some low cost mandatory policies include informative billing/real time usage feedback, combined with mandatory energy audits and reporting

Canadians are choosing to implement much of what is proposed above already. These areas of study were chosen because they were seen as a combination of “low hanging fruit,” being relatively easy to implement, and material, because in general these areas represent a large portion of Canada’s current GHG emissions.

As discussed earlier, the timing of GHG emissions reductions is important, not just the amounts, since cumulative emissions is tied to global warming. If the magnitude of total emissions reductions proposed here are imposed on the original graph of Canada’s historical emissions and our Paris conference targets, we see a major challenge in Figure 7.

Figure 7: Canada Greenhouse Gas Emissions and Targets: With "Easy Reductions"



* Source = Canada, “Canadian Environmental Sustainability Indicators: Progress Towards Canada’s Greenhouse Gas Emissions Reduction Target.” (Gatineau, 2017). Retrieved from https://www.ec.gc.ca/indicateurs-indicators/CCED3397-174A-4F0E-8258-91DCFE295B34/ProgressTowardsCanadaGHGEmissionsTarget_EN.pdf

The timing of the gentle nudge of programs discussed here results in a significant shortfall between performance and targets: they do not get us all the way there. However, Canada is not just making these small changes. Given the larger technical challenges of other potential areas of GHG reduction, an acceleration of any easier policies makes sense. In addition, there may be political and social feasibility to impose policies to speed up the progress.

Data shows currently manufacturers have followed vehicle emissions restrictions which will continue to be reduced to 2025. However, consumer preferences from 1990 to 2014 show car sales decreased by 8% while light truck sales increased 141%.[216] We are choosing bigger vehicles even though smaller and more efficient vehicles are offered on the market.

Data also shows solid progress in saturation of the market with high efficiency furnaces, energy efficient appliances, and other smaller home energy efficiency measures. Working against this trend however, is the uptake of many new, energy-gobbling appliances with GHG emissions increasing by 115% from 1990 to 2015 in this category; this is compared to large appliances, where GHG emissions fell by 45% in the same period.[217] Canadians continue to spend funds on energy-using entertainment and toys.

While our households have become more energy efficient, the average household itself has grown by 17% in area from 1990 to 2014.[218] Canada has an affluent and growing economy, and this is demonstrated in these numbers.

Not only are there technical, financial or economic barriers preventing the adoption of energy efficiency options, society also has deeply embedded social practices that shape energy use.[219] The forms of policy addressing values and routines that frame energy consumption rather than economic appeal alone require specific focus.[220] A strong dialog approach between stakeholders is needed to most effectively incorporate collective understandings of how the new technology will fit best and be absorbed into everyday practices.[221] Rather than implementing a limited number of specific policies that address very specific products, a joint discussion of everyday practices and energy savings opportunities enables both a deeper understanding of

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[216] Canada, Natural Resources Canada, “Energy Use Data Handbook Tables.”

[217] Ibid.

[218] Ibid.

[219] P. Webber, A. Gouldson, N. Kerr, “The impacts of household retrofit.”

[220] L. Vlasova, K. Gram-Hanssen, “Incorporating inhabitants’ everyday practices into domestic retrofits,” *Building Research & Information*, (2014), Vo. 42, Issue 4, pp.512-524. http://www.tandfonline.com/doi/abs/10.1080/09613218.2014.907682

[221] Ibid.

energy GHG reduction goals and a more thorough implementation of energy saving opportunities throughout a home or workplace.[222]

While the political will to impose a carbon tax exists, the current level of carbon tax, combined with current incentives and regulations, does not yet appear to be significant enough to move consumers quickly toward some the measures discussed here.

6.3 Final Word – Save Mankind Now or Save Mankind Later?

In considering that many of the recommendations we study here have solid financial justification, one asks why the adoption rate is not greater. In addition to many of the detailed reasons previously discussed, three main reasons have been highlighted in literature: the Jevons paradox, the median voter, and time-distorted preferences of voters and consumers.[223]

The Jevons paradox says that increased technological efficiency results in lower energy use. This lower energy demand results in a lower price. The subsequent lower fuel price results in an increased demand, at the new higher efficiency – essentially a rebound effect masking some of the gains of energy efficiency.[224] Some authors conclude the Jevons paradox shows efficiency policies are counter-productive.[225] The performance of the freight industry considered here shows how increased trade through a growing economy has lead to higher transport and related energy consumption levels, despite increases in efficiencies.

The policies put in place by politicians must be rationally aligned with the view of the median voter in order to obtain majority vote or acceptance. Thus, policies supporting higher taxation, regulated shrinking areas of the economy such as oil and gas, pipelines, or freight

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[222] Ibid.

[223] Matthias Klumpp, "To Green or Not to Green: A Political, Economic and Social Analysis for the Past Failure of Green Logistics," *Sustainability*, Vo. 8, Issue 5, (2016). https://doaj.org/article/290a518391cd46d191fdd1563573ab3b

[224] Ibid.

[225] Ibid.

transportation, must have majority support. At the same time, the median voter views the issues from their standpoint as consumer – voter preference will tend heavily toward lesser taxation or regulation, even if not optimal considering sustainable development.

The challenge of aligning implemented policies with voters is complicated when considering people have largely time-distorted and place-distorted preferences.[226] Consumers value consumption and wellbeing today and in the personal environment higher than in the future, and somewhere further afield. While support for wind power in general is strong, single consumers and voters do not want to be affected by the specific burden of windmills or power lines in their neighbourhood.

These issues combine to create a restricted field of possible action and support of GHG emissions policies, all of which trade the benefits of the current population for benefits of a future population.

These policies are focused on national and local issues, while the greater question is how do Canada's policies interact and align with other countries. The essential question in studying global warming is the recognition that not all countries enjoy the same level of economic success at this point in time, and economic growth is proportional to GHG emissions growth. In reducing poverty of a current generation through economic growth, the world impacts the future generations through climate change. Collins and Zheng call this the "Poverty-CO_2 Reductions Paradox."[227] Forcing developing nations such as China and India to reduce CO_2 emissions restrains their ability to rise out of poverty. The paradox is the choice between two terrible outcomes: people living in extreme poverty or catastrophic climate change impacts caused by

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[226] Ibid.

[227] D. Collins, C. Zheng, "Managing the Poverty-CO2 Reductions Paradox," *Organization & Environment*, Vol. 28, Issue 4, pp. 355-373 (2015). http://journals.sagepub.com/doi/10.1177/1086026615623059

increased CO_2 emissions. Collins and Zheng postulate self-interested people would not harm others to get what they wanted usually, due to self-regulating moral governance, a strong system of justice and government regulations. But when those we are harming are future generations, and the justice system is not built to encompass this temporal issue, general fairness and equity concepts apply.[228] The question is how can Canada connect the commitment to reducing future GHG emissions for future generations of Canadians with policy implemented today.

Essentially, the root of the Paris Agreement and similar global agreements focus on many small steps where short-term progress will likely be win-win and tradeoff approaches between countries, but longer-term policies will address the paradox issue. Moral boundaries and national fairness and justice will be considered in crafting some of the larger steps toward GHG emissions reduction to come.

The programs considered here address "easy" ways for Canada to potentially reduce some of its GHG emissions over the next twenty years. They represent Canada's first small steps toward deeper cuts in GHG emissions needed to meet Paris Agreement goals. While these policies will serve to engage more Canadians and potentially educate them regarding global warming issues, they barely scratch the surface of real changes required, and they remind us achieving largescale GHG reductions in order to affect global warming will not be "easy." Politicians must not become complacent that success in these areas are enough; much bigger steps and challenges to the paradigm of the Canadian way of life are required in order to attempt to meet both the timing and amount of GHG emissions reductions targets set in 2015.

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[228] Ibid.

Appendices:

Appendix 1: Estimated Current Fuel Prices – Used in Cost Savings Estimates

Table 32: Residential Electricity Cost Estimates - May, 2016

	Price per kWh, $ Cdn					
	kWh load					
	375	**750**	**1000**	**2000**	**5000**	Average
Calgary	$ 0.14	$ 0.12	$ 0.11	$ 0.10	$ 0.10	
Edmonton	$ 0.14	$ 0.11	$ 0.11	$ 0.09	$ 0.09	
Halifax	$ 0.18	$ 0.16	$ 0.16	$ 0.15	$ 0.15	
Moncton	$ 0.16	$ 0.13	$ 0.12	$ 0.11	$ 0.11	
Montreal	$ 0.09	$ 0.07	$ 0.07	$ 0.08	$ 0.08	
Ottawa	$ 0.19	$ 0.17	$ 0.17	$ 0.16	$ 0.15	
Regina	$ 0.18	$ 0.15	$ 0.15	$ 0.14	$ 0.13	
Saskatoon	$ 0.18	$ 0.15	$ 0.15	$ 0.14	$ 0.13	
Saint John	$ 0.14	$ 0.12	$ 0.11	$ 0.10	$ 0.10	
St.John's NL	$ 0.15	$ 0.12	$ 0.12	$ 0.11	$ 0.11	
Vancouver	$ 0.10	$ 0.10	$ 0.11	$ 0.12	$ 0.13	
Winnipeg	$ 0.10	$ 0.09	$ 0.08	$ 0.08	$ 0.08	
Average $/kWh	$ 0.15	$ 0.13	$ 0.12	$ 0.12	$ 0.11	**$ 0.124**

Source: Manitoba Hydro, "Energy Rates and Options, Utility Rate Comparison," price effective May 1, 2016. Accessed 2017-06-17. https://www.hydro.mb.ca/regulatory_affairs/energy_rates/electricity/utility_rate_comp.shtml#analysis

Table 33: Residential and Commercial Natural Gas Variable Cost Estimates - June, 2017

			Variable Costs		**Fixed Costs**	
Province	**Total Variable Price per GJ, June 2017**	**Total Variable Price per kWh, June 2017**	**A. Base variable[2] cost (distribution or delivery cost) $/GJ**	**B. Other variable[2] cost (commodity cost), $/GJ**	**Fixed[1] monthly cost $ (not used for analysis)**	**Sources**
Alberta	$ 3.40	$ 0.0122	$ 1.24	$ 2.16	$ 7.59	Gas Alberta - http://www.gasalberta.com/gas-market/gas-rates-in-alberta, Direct Energy - http://www2.directenergy.com/direct-energy-regulations-educational/about-your-rates/your-natural-gas-rates.aspx
NB	$ 17.97	$ 0.0647	$ 9.45	$ 8.52	$ 18.00	Enbridge Gas New Brunswick - https://naturalgasnb.com/en/for-home/customer-care/our-product-offering/#commodity-rate-history
NS	$ 18.11	$ 0.0652	$ 8.69	$ 9.42	$ 21.87	Heritage Gas - http://www.heritagegas.com/for-home/rates/
Ontario	$ 10.65	$ 0.0383	$ 7.70	$ 2.95	$ 20.00	Enbridge - https://www.enbridgegas.com/homes/accounts-billing/residential-gas-rates/purchasing-gas-from-enbridge.aspx, Ontario Energy Board -https://www.oeb.ca/rates-and-your-bill/natural-gas-rates
Average:	**$ 12.53**	**$ 0.0451**	**$ 6.77**	**$ 5.76**	**$ 16.87**	

1. Fixed costs = monthly cost to consumers, not dependent on volume of energy used. Variable costs = costs attributed per GJ.
2. Variable costs include commodity cost, distribution or delivery cost, as charged by natural gas providers

1.0 Gigajoule (GJ) = 26.853 cubic metres (m3)

Table 34: Commercial and Insitutional Electricity Cost Estimates - April, 2016

	Price Per kWh, $ Cdn						
	Small Power	**Medium Power**			**Large Power**		**Average**
Power demand	**40 kW**	**500 kW**	**1000 kW**	**2500 kW**	**5000 kW**	**50000 kW**	
Consumption	**10000 kWh**	**100000 kWh**	**400000 kWh**	**1170000 kWh**	**3060000 kWh**	**30600000 kWh**	
Load factor	**35%**	**28%**	**56%**	**65%**	**85%**	**85%**	
Montreal	$ 0.11	$ 0.14	$ 0.09	$ 0.08	$ 0.06	$ 0.06	
Calgary	$ 0.09	$ 0.09	$ 0.07	$ 0.05	$ 0.05	$ 0.05	
Charlottetown	$ 0.19	$ 0.20	$ 0.16	$ 0.16	$ 0.10	$ 0.10	
Edmonton	$ 0.10	$ 0.15	$ 0.10	$ 0.09	$ 0.07	$ 0.04	
Halifax	$ 0.18	$ 0.19	$ 0.15	$ 0.13	$ 0.12	$ 0.12	
Moncton	$ 0.15	$ 0.16	$ 0.13	$ 0.13	$ 0.09	$ 0.08	
Ottawa	$ 0.18	$ 0.17	$ 0.15	$ 0.15	$ 0.15	$ 0.05	
Regina	$ 0.15	$ 0.17	$ 0.13	$ 0.11	$ 0.10	$ 0.08	
St.John's NL	$ 0.12	$ 0.13	$ 0.10	$ 0.09	$ 0.09	$ 0.05	
Toronto	$ 0.20	$ 0.20	$ 0.16	$ 0.16	$ 0.15	$ 0.06	
Vancouver	$ 0.13	$ 0.13	$ 0.09	$ 0.09	$ 0.08	$ 0.07	
Winnipeg	$ 0.10	$ 0.11	$ 0.08	$ 0.06	$ 0.05	$ 0.05	
Average $/kWh	$ 0.14	$ 0.15	$ 0.12	$ 0.11	$ 0.09	$ 0.07	$ 0.113

Source: “Comparison of Electricity Prices in Major North American Cities,” Hydro Quebec, (2016).
http://www.hydroquebec.com/publications/en/docs/comparaison-electricity-prices/comp_2016_en.pdf

Table 35: Heating Oil Price Estimates - june, 2017

Monthly Average Wholesale (Rack) Prices for Furnace Oil (Rack) in 2017 (Cents per Litre)[1]				
Month of	**Canada**	**Calgary**	**Halifax**	**Toronto**
Jan-17	63.4	69.2	57.2	69.6
Feb-17	63	69.9	57.6	69.2
Mar-17	61.1	68.9	56.1	66.1
Apr-17	62.3	68.7	56.4	67.2
May-17	59.2	64.7	53.2	64.5
Jun-17	**55.3**	60.5	49.3	61.8
June, 2017 Canada Price converted to $ per GJ = $ 17.23/GJ				
Heating oil energy content = 38.2 MJ/litre				
Assumed furnace efficiency[2]= 84%				
1. Source: Natural Resources Canada, http://www2.nrcan.gc.ca/eneene/sources/pripri/wholesale_bycity_e.cfm?ProductID=15				
2. Source: "Heating With Oil," Natural Resources Canada, (2012), retrieved from http://www.housing.yk.ca/pdf/heating_with_oil_nrcan.pdf				

Table 36: Gasoline Average Retail Prices by Urban Centre

	Apr-13	**Apr-14**	**Apr-15**	**Apr-16**	**Apr-17**
	Regular unleaded gasoline at self service filling stations				
	cents per litre				
St. John's	127	136	109	102	134
Charlottetown and Summerside	130	138	105	100	110
Halifax	129	136	108	100	112
Saint John	127	135	106	97	111
Québec	135	138	111	102	115
Montréal	134	144	118	109	125
Ottawa	123	133	103	100	116
Toronto	126	135	105	102	116
Thunder Bay	134	143	107	104	119
Winnipeg	123	127	94	90	102
Regina	117	128	96	88	103
Saskatoon	117	131	97	90	102
Edmonton	106	118	93	84	104
Calgary	111	123	95	90	108
Vancouver	137	147	124	115	139
Victoria	126	136	118	106	129
Whitehorse	128	134	109	100	120
Yellowknife	139	139	114	108	119
Average	126	135	106	99	**116**

Note: Prices for the average retail prices tables are collected as part of the regular monthly Consumer Price Index (CPI) survey. Unlike the CPI, average retail prices cannot be used to measure pure price change over time. In a given month, retail prices may be averaged across products that vary by quality, brand and outlet. In addition, product characteristics are not held constant over time. The CPI should be used for the measurement of pure price change.

Source: Statistics Canada, CANSIM, table 326-0009 and Catalogue no. 62-001-X.

Last modified: 2017-05-19

Table 37: Diesel Fuel Average Retail Prices by Urban Centre

	Apr-13	Apr-14	Apr-15	Apr-16	Apr-17
	Diesel fuel at self service filling stations				
	cents per litre				
St. John's	134	142	115	96	121
Charlottetown and Summerside	136	146	117	99	114
Halifax	128	141	105	87	104
Saint John	132	139	111	92	110
Québec	139	145	120	101	112
Montréal	138	150	121	99	114
Ottawa	130	137	112	88	106
Toronto	126	137	113	88	107
Thunder Bay	.	.	.	.	.
Winnipeg	124	139	99	86	103
Regina	122	137	100	84	100
Saskatoon	123	142	102	83	98
Edmonton	115	129	98	83	103
Calgary	118	134	99	82	105
Vancouver	141	146	123	100	118
Victoria	135	140	115	94	114
Whitehorse	142	152	124	100	114
Yellowknife	136	142	121	100	119
Average	130	141	112	92	**109**

. : not available for any reference period.

Note: Prices for the average retail prices tables are collected as part of the regular monthly Consumer Price Index (CPI) survey. Unlike the CPI, average retail prices cannot be used to measure pure price change over time. In a given month, retail prices may be averaged across products that vary by quality, brand and outlet. In addition, product characteristics are not held constant over time. The CPI should be used for the measurement of pure price change.

Source: Statistics Canada, CANSIM, table 326-0009 and Catalogue no. 62-001-X. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ154b-eng.htm

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