CHEMINFO

Powering GHG Reductions Through Technology Advancement

Final Report

Prepared For:

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1. Executive Summary

1.1 Recommendations

Canada can benefit economically while achieving reductions in greenhouse gas (GHG) air emissions though strategic technology advancement. This study identifies available technologies that can be applied to reduce non-energy related GHG emissions while offering economic benefits. However, the level of GHG emissions reduction that can be practically achieved with existing, low cost or benefit-providing technologies is limited. To achieve higher reduction levels, approaching the targets established for Canada in the Kyoto Protocol, broader application of more expensive options is required. Technology advancement, through product and process research, as well as marketing initiatives are required to improve technical features, lower the costs and increase the adoption of technologies addressing GHG emissions.

With many potential development requirements and limited resources, Canadian technology advancement strategies need to leverage existing strengths and experience in such areas as agriculture, landfills, forestry, pulp and paper, and oil and gas production, as well as develop technologies in a few niche industrial areas. To effectively meet GHG reduction targets, Canada's technology development strategy needs to take into account our unique economic structure and comparative capabilities in a rapidly evolving international field.

Recommendations for Environment Canada's Clean Technologies Advancement Division are:

1 Manage GHG emissions from landfills;
   - focus on large and medium sites,
   - develop technologies to lower reduction costs for all sizes of sites,
   - assess site approvals process to streamline and reduce "red-tape",

2 Develop niche GHG reduction opportunities with industry;
   - assess product substitutions (fly ash, slags in cement, HFCs),
   - identify and develop new applications for CO_2 and carbonates,
   - enhanced oil recovery,
   - aluminum, magnesium, nitric acid, petrochemicals, etc.,

3 Increase involvement in agricultural sector;
   - demonstrate and promote aerobic manure composting and anaerobic digesters
   - promote optimal fertilizer application,
   - develop measures to track GHG reductions,

4 Increase involvement in forestry sector.
   - partner with Natural Resources Canada and Canadian Forestry Services to promote and export know-how.

1.2 Emissions and Trends

Non-energy GHG emissions covered in this study total 113.6 megatonnes (Mt) of carbon dioxide (CO_2) equivalent[1]. Approximately half of these emissions originate from agricultural sources, namely: enteric livestock fermentation; manure decomposition; and fertilizer application. Thousands of landfills across Canada contribute 19% of total estimated emissions investigated. Most other non-energy emissions result from various industrial sources, and consumption of refrigerants and other chemicals with high global warming potential (GWP).

Table 1-1: Non-Energy Emissions Covered in This Study

(does not include all non-energy emissions sources)

Areas	1990 (Mt)	1995 (Mt)	% 1995
Agriculture[2]	50	53.2	47%
Landfills[3]	20	21.5	19%
Adipic acid	11	10.9	10%
Lime kilns[4]	10	10.0	9%
Aluminum (CO_2 and PFCs)	9	9.2	8%
Petrochemicals	4	4.7	4%
HFCs, SF_6, PFCs uses	3	3.0	3%
Nitric acid	1	1.1	1%
Total *	108	113.6	100%

* Total emissions differ from Environment Canada non-energy inventory of 97.7 for 1990 and 102.4 Mt for 1995. 1990 area estimates calculated based on percentage changes between 1990 and 1995 established in Environment Canada's "*Trends in Canada's Greenhouse Gas Emissions*"

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[1] For certain source areas, these emissions differ slightly from Environment Canada estimates published in the report "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", April 1997. For some sources, estimates of GHG emissions were made to satisfy the objectives of this study which had a technology development and application perspective.

[2] Includes CH_4 and CO_2 from livestock, CH_4 from manure and N_2O from fertilizer application. An extra 28 Mt of CO_2 livestock emissions has been included in this category. In Environment Canada's 1995 inventory, these emissions are believed accounted for in the agricultural soils Century model (see pg. 52 of Environment Canada's "Trends" report).

[3] Includes an extra 3.3 Mt of CO_2 emissions from landfills. In Environment Canada's GHG inventory, these emissions are believed to be accounted for in the Carbon Budget Model of the Canadian Forest Sector (see pg. 56 of Environment Canada's "Trends" report).

[4] Includes CO_2 generated specifically from pulp mill lime kilns. Pulp mill lime kiln CO_2 emissions are believed to be accounted for in the Spent Pulping Liquor category of Biomass Combustion (see pg. 60 of Environment Canada's "Trends" report).

1.2.1 Trends in Emissions

Non-energy GHG emissions are expected to increase by 9% to 22% between 1995 and 2010 in the "business as usual scenario". With 1995 emissions already 5% higher than 1990 levels, the total overall reduction necessary to meet Kyoto Protocol targets will need to be in the range of 14% to 27% (from 1990 levels). One major achievement, already realized, is DuPont Canada's reduction of N_2O emissions from adipic acid production, using catalytic reduction technology.

Table 1-2: Estimated Growth in Emissions Between 1995 and 2010

Area	**1995 Emissions**	**Low Growth**	**High Growth**	**Low**	**High**
	(Mt)			(Mt)	(Mt)
Agriculture	53.2	20%	30%	63.8	69.2
Landfills	21.5	20%	30%	25.8	28.0
Adipic acid	10.9	(95%)	(90%)	0.5	1.1
Lime kilns	10.0	5%	10%	10.5	11.0
Aluminum	9.2	5%	10%	9.7	10.1
Petrochemicals	4.7	40%	60%	6.6	7.5
SF_6, HFCs, PFCs,	3.0	100%	250%	6.0	10.5
Nitric acid	1.1	10%	20%	1.2	1.3
Total / Overall	**113.6**	**9%**	**22%**	**124.1**	**138.7**

Source: CHEMinfo Services estimates, Environment Canada estimates

Moderate growth in emissions is expected from agricultural sources, landfills and most industrial processes. However, new petrochemical capacity, especially in Alberta will boost GHG emissions. In addition, the phase-out of HCFCs under the Montreal Protocol on Ozone Depleting Substances will increase the demand and emissions for HFCs by 2010[5].

1.3 Overview of Technologies Investigated

This study encompassed an investigation of approximately 80 to 90 technologies in 13 non-energy related GHG source, sink, and reservoir areas. The list of technologies is not all-inclusive. There are many more technologies and instruments in various stages of development that are cross-cutting within non-energy GHG emission areas. These include applications of information technology (IT), biotechnology, and market instruments (in conjunction with facilitating technologies) that motivate production and consumption behaviours.

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[5] The Framework Convention on Climate Change does not include CFCs and HCFCs, although they do contribute to global warming. Therefore emissions of these gases are not included in this analysis.

Table 1-3: Non-energy GHG Reduction Technologies Investigated

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1.3.1 Livestock: Enteric Fermentation

Ruminant (e.g., cattle, sheep) and non-ruminant (e.g., swine, horses) agricultural livestock generate methane emissions. In Canada, beef cattle represent the majority of such emissions, due to the size of the herd population and the high emission rates per head (versus swine, horses, etc.). Poultry contribute negligible amounts of enteric methane emissions.

Technologies identified in this study which can reduce the amount of methane and carbon dioxide emitted from livestock include: greater use of feed additives (e.g., ionophores, antibiotics); steroid implants; improved livestock management and feeding practices; and bioengineering. All of these technologies and practices increase the production of milk or meat in relation to the amount of feed utilized or other resources employed. Various segments of the livestock population have different cost and benefit structures associated with various GHG reduction strategies. Application of low cost additives (e.g., ionophores) can result in savings for feed and provide yield benefits for some portions of the livestock population. However, not all portions of the livestock population will be suitable to one solution. For example, ionophores are not suitable for swine.

Applying ionophores (as an example) to livestock not already using the product, can result in a 4 to 5% reduction in GHG emissions from all livestock in Canada (includes methane and carbon dioxide) while providing economic benefits through increased milk and meat production. This technology needs to be considered under a holistic livestock management program to achieve greater GHG reduction levels from the sector.

1.3.2 Livestock: Manure

The majority of the research to date on technologies to reduce methane (CH_4) emissions from livestock manure has centered on aerobic composting and anaerobic digesters. Currently there are no anaerobic digesting or aerobic composting systems in use in Canada. There are approximately 10 firms in Canada developing variations of aerobic composting systems. Most of these firms are in the process of demonstrating pilot scale systems. Several firms have been approached by interested Canadian as well as U.S. farmers to determine system cost and availability.

Aerobic composting has the potential to mitigate GHG releases from two sources. First of all, aerobic composting, through the utilization of manure to produce an organic fertilizer, reduces methane emissions (i.e., greater than 50%). Secondly, the organic fertilizer has the potential to replace commercial chemical fertilizers. Organic fertilizers are much more stable than chemical fertilizers and are much less prone to leaching of nitrogen compounds either downward into the soil or upward into the atmosphere. One prominent Canadian technology developer suggests that organic fertilizers produced through aerobic composting have the potential to "substantially" reduce dependence on chemical fertilizers.

Approximately a decade ago, 10-15 anaerobic digesters were installed at Canadian farms. However, they all failed due to the fact that: (i) the program promoting these digesters was canceled eliminating technical support for the farmers; (ii) many of the digesters broke down after a short period; and (iii) the cold climate in Canada reduced the economic feasibility of the digesters. Currently, there are no known anaerobic digesters operating at Canadian farms.

Manure management systems that store manure under anaerobic conditions contribute about 60% of the CH_4 from anaerobic decomposition of organic materials. It has been shown that anaerobic digesters can reduce emissions by up to 70-80%. Digesters have become much more efficient and technologically advanced over the last decade. However, more R&D and demonstration of newer systems are required to increase adoption in Canada.

Applying aerobic composters and anaerobic digesters to address manure emissions needs to first focus on large farms. The AgSTAR program (EPA's manure management program) estimates that over 2,000 livestock facilities across the U.S. could install cost effective biogas recovery systems. Most, if not all, digesters operating in the U.S. are located at dairy or pig farms. There are several European poultry farms with anaerobic digesters. In Canada, there are 28 reported farms with more than 300 dairy cows and 1,145 farms with more than 2,000 pigs. However, some of the smaller farms (i.e., the 1,134 Canadian farms with between 100 and 300 dairy cows as well as the 1,855 Canadian farms with between 1,000 and 2,000 pigs) may also be viable candidates. It is unclear if feed lots which house a large number of beef cattle could also be viable candidates for anaerobic digesters. More research and development is required in this area.

Agriculture and Agri-Food Canada is currently funding research on aerobic composting of hog manure as well as bioreactors that reduce CH_4 emissions from manure. Both of these technologies along with anaerobic digesters are promising as cost effective tools to reduce CH_4 emissions from livestock manure.

1.3.3 Fertilizer Application

A wide variety of farm management practices and technologies, developed or in the development stage, can reduce N_2O emissions from fertilizer application. The IPCC has estimated that N_2O emissions from agriculture could be reduced by 9-26% by improving agricultural management with available techniques. Using an estimate of a 22% reduction for Canada results in a 3 kt reduction in N_2O emissions or approximately 900 kt of CO_2-

equivalent. This is a low capital and operating cost option (+/-5 \$/tonne-CO_2 reduced has been assumed). Growers are likely to realize benefits through lower fertilizer costs.

Many of the existing technologies and practices have been adopted by a small portion of the farming community and have resulted in a net economic benefit to some farmers. Canadian farmers could therefore potentially reduce a significant portion of their N_2O emissions from fertilizer application at little or no economic cost. To maximize the application of current and future farming practices and technologies, more research is required to ensure that the various approaches are refined to the point that farmers will be more receptive to their adoption. AAFC has indicated that they do not expect the necessary level of funding to be made available to conduct the required research and development in the future. Environment Canada may have a role to play to ensure that the current technologies and practices are refined and adopted and that some of the evolving technologies are improved so that they too are adopted by the Canadian farming community.

1.3.4 Landfills

Potential GHG emissions from landfills for 1995 are estimated at 27.2 Mt. However, actual emissions were 21.5 Mt, with 18.2 Mt of that total being methane (expressed as CO_2-equivalent in terms of global warming potential).

The costs to reduce GHG emissions from landfills relate to the level of emissions reduction desired, as well as the technology options adopted. A low cost option to achieve a 20 to 30% reduction is to capture, collect and flare (i.e., burn) the methane generated from the largest sites. This option has no associated direct financial incentive. Some of the landfills generate enough methane to support a larger investment in gas utilization equipment. Gas utilization projects are more capital intensive but can provide a return to investors, through sale of the electricity or fuel. The greatest portion of the costs in achieving a higher (10 to 20% more) level of GHG reduction is associated with reducing emissions from thousands of small landfills spread across Canada. Even flaring or establishing aerobic landfill conditions at these sites could cost hundreds of millions of dollars in capital. Therefore, recommendations to address GHG from landfills are as follows:

- focus on medium and large sites;
- optimize gas collection and utilization for systems already installed;
- assess feasibility of sites with potential for landfill gas utilization;
- encourage synergistic direct-use situations (e.g., gas users near landfills); and
- support development of technologies and practices that increase collection efficiency, gas treatment and other technologies that reduce capital and operating costs for all sites.

1.3.5 Adipic Acid

A significant reduction of nitrous oxide (N_2O) emissions from adipic acid production has already occurred through the development and installation of a catalytic reduction technology for the only adipic acid plant in Canada, owned by DuPont Canada in Maitland, ON. An estimated 30 kt/yr of N_2O emissions (9,300 kt CO_2 equivalent) have been reduced from 1995 levels of 35 kt/yr for a total capital cost of about $15 million. Further marginal reductions are being achieved through improvements in operating efficiency. On an annualized basis, the total cost of reduction is calculated as $0.2 per tonne of CO_2 equivalent reduced.

1.3.6 Lime Production

Lime kilns are found in cement plants, kraft pulp mills, and iron and steel mills which use lime internally in their production processes. Commercial producers sell lime to these industrial sectors as well as a to broader merchant market. Carbon dioxide is emitted from lime kilns by the calcining (heating to drive off hydrated water) of calcium carbonate (limestone). Although some of the carbon dioxide from lime kilns could be used internally at sites, most kilns have no alternative disposition. Therefore, reducing emissions from lime kilns requires analysis of various approaches. One approach relates to technologies that address emissions through reductions in lime consumption in major applications, such as cement, iron and steel, and pulp and paper. Another approach is to control carbon dioxide emissions with the installation of capture, treatment and extraction equipment. The extracted carbon dioxide would then need to be sequestered in reservoirs to prevent releases to air.

There are many areas that require research and development support with respect to carbon dioxide emissions from lime kilns. Areas include reduction in lime requirements in application markets, as well as developing a better understanding of the sequestering of carbon dioxide that could be captured and extracted directly from lime kilns. Specific research and development areas for consideration include:

- substitutes, such as fly ash or slags, for clinker in cement;
- pulp and paper mill changes that reduce use of carbon dioxide;
- separation technologies at lime kiln operations; and
- sequestering technologies and carbonates (or other) production development.

1.3.7 Petrochemicals

The petrochemical industry in Canada includes two broad areas covered in this study, namely the use of natural gas liquids (NGLs) and crude oil based liquid feedstocks for the production of ethylene and co-products (i.e., propylene, butadiene, etc.) in large scale facilities; and use of natural gas - methane - for the production of ammonia, urea and methanol. These two areas account for the majority of GHG emissions associated with "non-energy" uses of natural gas and natural gas liquids from the petrochemical sector.

Technologies analyzed in this report include the following:

Petrochemicals based on natural gas liquids and crude oil based feedstocks

- alternative feedstocks;
- furnace anticoking additives;

Petrochemicals based on natural gas - methane - feedstock

- increased production of urea using ammonia and carbon dioxide;
- increased production methanol using available hydrogen and carbon dioxide; and
- improvements in energy and yields.

Achieving reductions in emissions from the petrochemicals sector approaching the targets set out in Kyoto presents strong challenges for Canada's petrochemical industry. Some of the technology options identified in the study require additional research and development, and more detailed analysis on several dimensions. Emissions from the petrochemical industry will need to encompass energy as well as non-energy sources of carbon dioxide, since these are inextricably linked at individual facilities and within large complexes.

1.3.8 Nitric Acid Production

The emissions of N_2O from nitric acid production in Canada are concentrated at one site. Eight of nine existing nitric acid plants have catalytic reduction technologies already installed which are assumed to control N_2O emissions to low levels. There is potential to control N_2O emissions from the remaining existing facility, and additional N_2O emissions from a new plant that has been recently installed at the same site. Use of non-selective catalytic reduction (NSCR) technology can achieve an estimated overall reduction of 60% of total N_2O emissions with associated costs of approximately $400 per tonne of N_2O reduced, or $1.3 per tonne of CO_2 equivalent.

1.3.9 Aluminum Production

Two different greenhouse gas emissions originate from the anode in smelting pots in the primary aluminum production industry. In 1995, an estimated 3,600 kt of CO_2 was emitted from the consumption of carbon anodes and another 5,600 kt of CO_2 equivalent was emitted as PFCs formed in anode events. These emissions come from 11 smelters which employ a range of smelting technologies. Better process control and carbon anode baking technology can reduce CO_2 emissions by a small percentage, assumed to be only 5%. Research into inert anodes which would eliminate CO_2 emissions is being conducted, but development is expected to be longer-term. Improved alumina feed process control can reduce PFC generation by 10-50%.

1.3.10 Magnesium Production

The primary and secondary magnesium industry is the largest source of SF_6 emissions in Canada, accounting for an estimated 75 tonnes of SF_6 in 1995, or about 1,900 kt/yr of CO_2 equivalent. SF_6 emissions come from its use as a component in cover gas in two magnesium smelters (Norsk Hydro and Timminco) and 5-10 magnesium diecasters.

The Norsk Hydro plant in Becancour, QC is a world-scale sized magnesium facility and is the largest of all the sources. A doubling of capacity at this plant in the next few years will increase SF_6 emissions in the short term. SF_6 emissions have been steadily reduced by applying better process control at the smelters. Norsk Hydro is performing research in Norway on an SO_2 cover gas system, which is planned to replace SF_6 within about 10 years. A 10% reduction through better process control is achievable at low unit costs (i.e., ~$1.9/t CO_2 equivalent reduced).

1.3.11 HFCs, SF_6, PFCs Uses

SF_6, PFCs and HFCs are used in many applications other than in primary metal manufacture. The total estimated emissions of three gases in other uses is approximately 1,000 kt of CO_2 equivalents. (Some of these emissions have not been identified in Environment Canada's 1995 inventory). Roughly half of the estimated emissions are accounted for by HFCs used in air conditioning and refrigeration applications. High growth in emissions is expected with the scheduled phase-out of HCFCs[6] by 2020.

In most HFC applications, there are several alternatives, but few which have been commercialized. Hydrocarbon refrigerants (propane and iso-butane) represent the most commonly used alternative. For SF_6, the use of air or vacuum circuit breakers, better leak detection and repair programs, and capture and recycle systems represent the most feasible technologies. For PFCs, capture and recycle systems and substitution with lower-GWP hydrofluoroethers (HFEs) represent current choices.

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[6] The Framework Convention on Climate Change does not include CFCs and HCFCs, although they do contribute to global warming. Therefore emissions of these gases are not included in this analysis.

1.3.12 Carbon Sequestration in Biomass

There are upwards of 25-30 different forest management practices that sequester carbon (C) in Canada's biomass. The most common of these practices are reforestation of previously stocked land, afforestation of land that has historically not been forested, and the use of forests as a bioenergy source to offset fossil-fueled based GHG emissions.

Forest management practices could be among the most cost-effective tools with which countries can meet their respective GHG emissions targets. Many reforestation and afforestation cost estimates are in the range of $5 to 15 per tonne of CO_2 removed. Depending on various forest management scenarios, and the amount of land addressed, carbon dioxide reductions of 1% to 145% of Canada's total annual carbon dioxide emissions (461,000 kilotonnes in 1995) can theoretically be achieved. As a reference point, costs to achieve 13,400 kilotonnes of emission reductions annually (i.e., 3% of total emissions), would cost approximately $134 million annually (@$10 per tonne-CO_2).

1.3.13 Underground Storage: Enhanced Oil Recovery

Carbon dioxide can be stored underground in rock structures and aquifers. This type of disposition represents a reservoir (as opposed to a sink) for carbon dioxide which remains in the ground, under pressure, thousands of feet below the surface. A practical application of this option is the use of CO_2 for enhanced oil recovery (EOR) at partially depleted oil reservoirs in Western Canada. From this application, technology and cost implications for broader application of underground storage can be inferred.

EOR represents a reduction option for large point sources of carbon dioxide emissions such as ammonia plants, electrical power facilities, ethylene petrochemical plants and other sources where the amount of CO_2 that can be captured, treated, extracted and transported via pipeline to an underground storage reservoir is large enough to justify the high capital costs in infrastructure.

Although there is only one small commercial carbon dioxide EOR project operating in Canada, more are anticipated. In 1997, PanCanadian Petroleum, of Calgary and 36 partners announced a project to use carbon dioxide to enhance crude oil production from the Weyburn oil fields in Saskatchewan. In 1998, Dakota Gasification plans to start construction of a $140 million pipeline to transport carbon dioxide from Beulah, ND to Weyburn, SK, a distance of close to 325 kilometers. The source of the carbon dioxide is the Great Plains synfuel plant at Beulah, ND. Carbon dioxide gas consumption for this project is expected to average 5.5 kilotonnes per day, or nearly 2,000 kt per year. Over the life of the project a total of 30,000 kt of carbon dioxide will have been stored. The result will be an increase in oil production from the field from 18,000 barrels to 30,000 barrels per day by the year 2008.

1.4 Costs to Reduce Non-energy GHG Emissions

The cost analysis for this study provides order-of-magnitude estimates for capital and operating expenditures associated with adoption of some of the technologies researched. Costs could not be prepared for all 80 to 90 technologies identified and investigated. Therefore, cost totals are not representative of total industry or social costs to reduce GHG emissions.

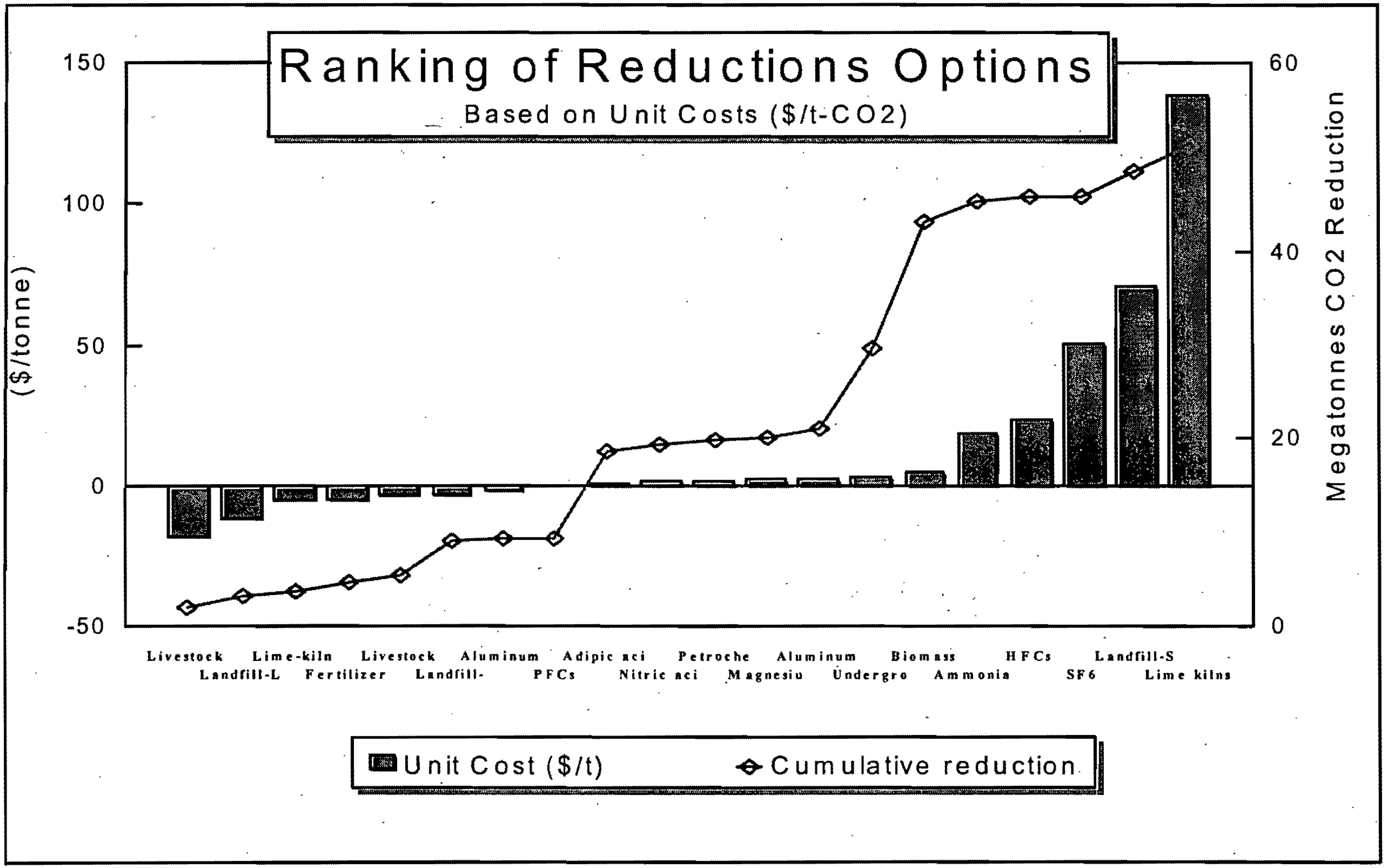
Table 1-4: Overview of Annualized Costs to Achieve Reductions With Selected Technologies

(Capital and net operating, low cost scenarios)

	Capital	Operating	Total	Mt GHG Reduction	Reduction Levels	Capital	Operating	Total
		($ million)			(See Notes)		($/t-CO2)	
Non-energy	$338	$220	$558	29	26%(1)	$11.6	$7.5	$19.1
Underground storage (EOR)	$540	($515)	$26	9	7%(2)	$63.0	($60.0)	$3.0
Biomass carbon sequestration	$0	$67	$67	13	19%(3)	$0.0	$5.0	$5.0
Total				51	45%(4)			

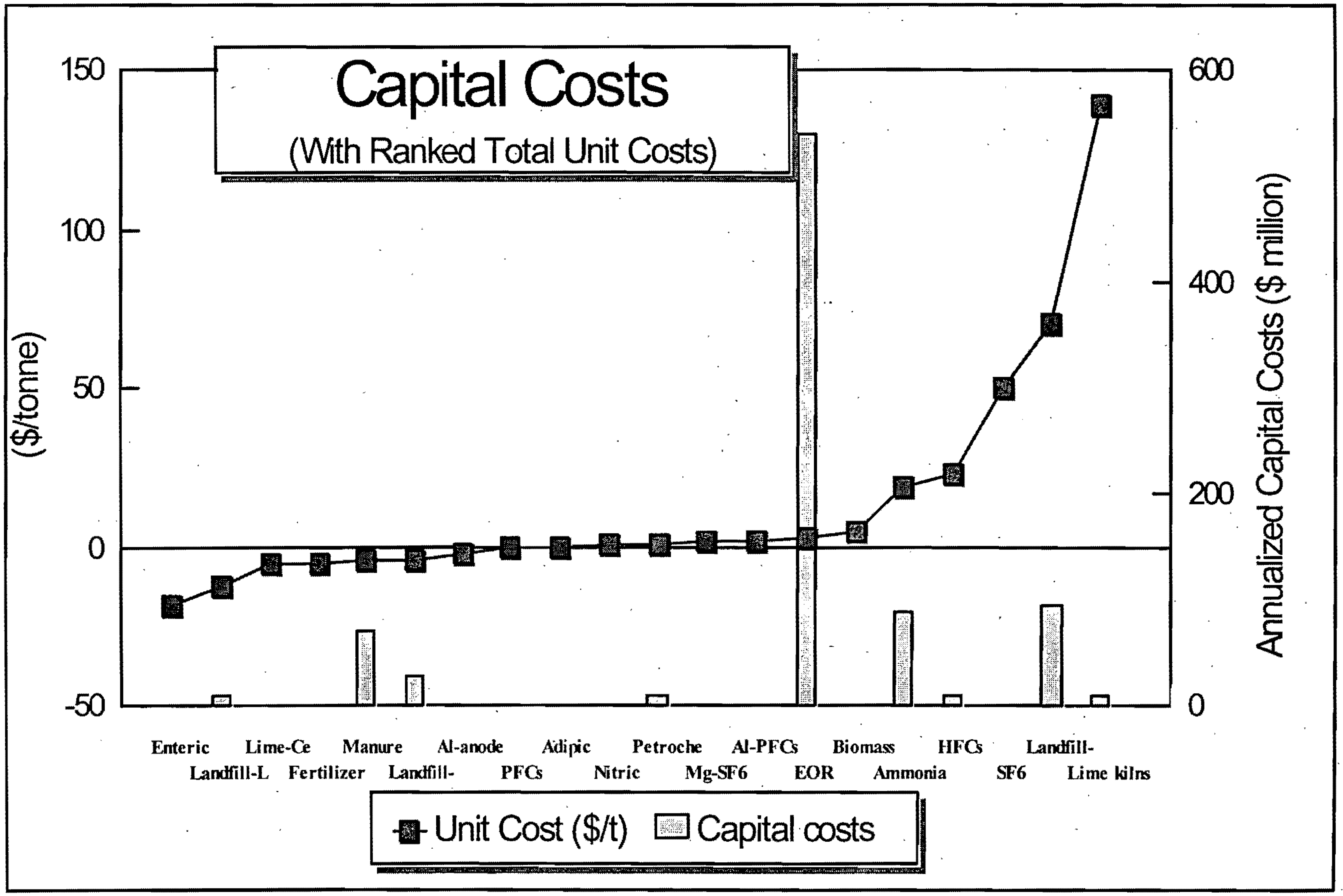
1. 26% of total non-energy GHG emissions covered in this study.
2. 7% of major sources (energy and non-energy) in Western Canada
3. 19% of 67 Mt potentially achievable target.
4. 45% of total non-energy emissions covered in this study.

Some technologies can provide economic benefits, but have high capital costs (and costs of capital higher than assumptions used for this study - i.e., 10% interest rate) that present barriers to adoption. The attractiveness of various technologies for development purposes or for adoption will be influenced by the total capital investment required to bring about a reduction. From a capital cost basis, the most attractive areas include: product substitution for perfluorocarbons (PFCs); substitution of fly ash, slags and other suitable materials for cement clinker; farm practices to reduce fertilizer use; and biomass sequestration tactics such as reforestation and afforestation.



Ranking of Reductions Options

Based on Unit Costs ($/t-CO2)


Capital Costs
(With Ranked Total Unit Costs)
($/tonne)
150
100
50
0
-50
Annualized Capital Costs ($ million)
600
400
200
0
Enteric
Landfill-L
Lime-Ce
Fertilizer
Manure
Landfill-
Al-anode
PFCs
Adipic
Nitric
Petroche
Mg-SF6
Al-PFCs
EOR
Biomass
Ammonia
HFCs
SF6
Landfill-
Lime kilns
Unit Cost ($/t)
Capital costs

Areas which require more research and development to lower capital costs in the application of the technologies includes: lime kilns; small landfills; ammonia plants; digesters for livestock manure; and underground storage (with or without enhanced oil recovery). These areas feature such problems as dilute carbon dioxide gas streams, fragmented pattern of emissions, lack of infrastructure and lack of markets. They present development challenges which need to be overcome for Canada to achieve reductions from non-energy sources approaching Kyoto targets.

Unit reduction costs (\$/tonne-CO_2) developed for this study are useful for ranking various options. However, these costs reflect chosen technologies, and may not be representative of the best technologies (energy and non-energy) that could be applied in each of the emitting sector areas.

1.5 R&D Capabilities and Requirements

In a few selected areas Canada's R&D status and capabilities are already strong. Fortunately, some of these strengths lie in areas that are major sources and sinks of GHG, namely the agricultural sector, forestry and pulp and paper, and oil and gas production. In many other areas, Canada's R&D capabilities are weaker, and in some cases practically non-existent with respect to technologies associated with reducing GHG emissions from non-energy areas.

Table 1-5: Overview of R&D Capabilities in Canada

(in context of GHG technologies investigated)

Areas	Corporations	Industry R&D Centres	Government R&D Centres	Universities
Agriculture	●●	●●●	●●●●	●●●●
Landfills	●●	●	●●	●
Adipic acid	●●	●	●	●
Lime kilns	●	●	●	●
Aluminum	●●●	●	●	●●
Petrochemicals, other chemicals	●●	●	●	●
SF_6, HFCs, PFCs	●●	●●	●●	●●
Nitric acid	●●	●	●	●
Biomass sequestration	●	●	●●●●	●●●
Underground storage (EOR)	●●	●●	●●	●●

Legend:	•	very weak or non-existent
	••	some research conducted
	•••	strong research capability
	••••	very strong, among world leaders in field

Given the dynamics of global competition in many industrial areas, Canadian subsidiaries have access to R&D centres of their parent companies. For multi-national enterprises, these R&D centres are often located near the parent head-offices. Examples of this structure of R&D supply and demand include technologies (and associated GHG emitting sectors) in the following areas: gas separation needed for lime kilns and other areas; cement; catalyst technologies (adipic acid, nitric acid); magnesium production (SF_6); and refrigerants (HFCs). There are "pockets" of R&D activities in most of these fields carried out in Canada. However, the overall mass of activity and resources available are low in comparison to what is carried out internationally.

1.6 Secondary Environmental Benefits

Some technologies that address non-energy related GHG emissions provide secondary environmental benefits. Although the focus on this study was not to work out the environmental impacts of applying GHG reduction technologies and practices, there are examples where the secondary environmental benefits are evident. Specific examples include:

Livestock: Enteric Fermentation

⇒ Ionophores

  - increased efficiency of feed utilization
  - increased production within shorter period of time (with less feed)

Livestock: Manure

⇒ Covered Lagoons

  - gas used to generate electricity, heat water, and even to run chillers
  - reduce odour
  - minimize surface and ground water contamination

⇒ Large Scale Digesters

  - destruction of viruses, protozoa, and other disease-transmitting organisms
  - reduction in the potential for ground and surface water contamination
  - odour reduction

Fertilizers

⇒ Fertilizer Management Practices

  - decreased surface and groundwater contamination
  - improved crop yield (and plants consume CO_2)

Landfill Gas

⇒ Gas Collection and Treatment

  - removal of particulate, water, corrosive compounds, and other impurities
  - gas used to generate electricity or used for heating

Lime Production

⇒ Pulp and Paper Production: Ethanol Based Pulping

- elimination of malodorous sulphurous compounds
- elimination of recovery furnace
- use of recovered lignins for furfural, lignosulphonates, or acetic acid production
- elimination of caustic/sulphur chemical recovery process including elimination of the lime kiln

⇒ Pulp and Paper Production: Oxygen Delignification

- lower total bleaching agents required

⇒ Merchant Lime Producers: Gas separation (cryogenic, adsorption, membranes)

- particulate matter, water and other contaminant removal

Carbon Sequestration in Biomass

⇒ Management of Logging

- "Logging residues and timber processing by-products (including bark, sawdust and ships) are currently being utilized as bioenergy in many countries This impacts the amount of fossil-fuel (oil and gas) based energy that needs to be produced."

⇒ Urban Forestry

- windbreaks can save about 15% heat energy (thus reducing CO_2 from power generation from fossil-fuels)

Although some areas provide evident environmental benefits, the impacts of applying technologies usually involve trade-offs between conflicting environmental objectives (e.g., greater emissions of smog precursors versus lower GHG emissions). Some technologies require life-cycle analysis to ensure that net environmental and socio-economic benefits are maximized.

2. Introduction

2.1 Background

Scientific evidence, including work published by the Intergovernmental Panel on Climate Change (IPCC) has determined that there is a causal relationship between greenhouse gas (GHG) emissions and the global warming effect. In 1995, Canada contributed 619 megatonnes (Mt) of GHG emissions, which represents approximately 2% of the global total. Carbon dioxide (CO_2) is the primary GHG, representing 81% of total GHG emissions in Canada. However, there are other significant contributing pollutants to total GHG emissions, including methane (CH_4) and nitrous oxide (N_2O). The most significant source of GHG emissions is through the combustion of fossil fuels such as oil, gas and coal. Energy-related emissions contribute approximately 83% to total GHG emissions in Canada. Non-energy GHG emissions contribute the remaining 17% and are the focus of this study. Non-energy related emission sources include industrial sectors, agricultural practices, waste from landfills, and a number of applications which use a variety of GHG emitting chemicals.

Canada was one of over 150 countries to sign the Framework Convention on Climate Change at the United Nations Conference on Environment and Development in Rio de Janeiro in June, 1992. More recently, the Third Conference of the Parties met in Kyoto, Japan in December 1997 to agree on a future stabilization and reductions. The agreement calls for a 5.2% reduction in all greenhouse gases from 1990 levels by the period 2008-2012; Canada's binding target is a reduction of 6%, along with Japan, while the US agreed to a 7% reduction and the European Union committed to an 8% reduction[7].

If no changes were made, it is predicted that Canada's GHG emissions would steadily increase to a level where a 30% reduction would be required from 2010 levels to achieve the target. This is a substantial level of reduction. Some of the technologies researched and evaluated in this study have the potential to achieve a 30% or greater reduction in some areas. Many other technologies were also researched which offer lower levels of reduction.

Sinks, defined as a process or activity that removes a greenhouse gas from the atmosphere, have also been included as part of the Kyoto agreement, but only in a limited manner. The agreement states that net changes from sources and removals by sinks resulting from land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990 and measured as verifiable changes in stocks in each commitment period shall be used to meet the commitments [outlined in Article 3][8]. As a result, this report covers forest and soil management

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[7] Environment Canada, A. Jaques

[8] Ibid

practices which may assist Canada in meeting its obligations. In addition, this study describes underground injection for enhanced oil recovery. Although this is not a sink, it does provide for the potential of long term storage of carbon dioxide emissions.

2.2 Objectives of This Study

This study had the overall objective of providing information, analysis and recommendations to assist Environment Canada's, Clean Technology Advancement Division - Technology Development Branch, and potentially other government stakeholders involved in developing strategies and tactics to reduce GHG emissions while maximizing domestic economic potential available through technology advancement. The study had the following objectives:

1. identify and characterize technologies available to address climate change with respect to costs, stage in development, markets, suppliers, research and development status and requirements;
2. establish as precisely as possible the national GHG reduction potential and their associated costs for the selected sectors contributing to GHG emissions;
3. identify economic opportunities as well as non-GHG environmental benefits associated with advancing climate change technologies; and
4. identify the issues and barriers to technology advancement.

2.3 Scope of the Study

This study focused on non-energy related sources of GHG emissions. Environment Canada's report entitled *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* provided a guide, since it documents most of the non-energy industrial sectors, municipal and agricultural GHG emission sources. However, in addition to the source categories and emission estimates provided by Environment Canada, research and analysis in this study resulted in the identification of some new sources of emissions and required different estimates of GHG emissions in a few areas (in context of technology applicability and potential to achieve GHG reductions). This report did not have the objective of developing an inventory of GHG.

Reduction technologies were identified to address all the important pollutants that have global warming potential (GWP). These are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), carbon tetrafluoride (CF_4), carbon hexafluoride (C_2F_6), and the chlorofluorocarbon (CFC) substitutes not controlled by the Montreal Protocol on Ozone Depleting Substances - i.e., the hydrofluorocarbons (HFCs).

Scope of Non-Energy GHG Emission Areas Studied

Area	Segment / Sources
Agriculture	Enteric fermentation, livestock manure, fertilizers
Landfills	Large, medium, small
Lime kilns	Cement, pulp and paper, merchant lime suppliers
Aluminum	Carbon anodes, PFCs
Adipic acid	Production process
Nitric acid	Production process
Petrochemicals	Methane, NGLs, crude oil based feedstocks
SF_6, HFCs, PFCs,	Magnesium, refrigerants, special chemical uses
Biomass sequestration	Reforestation, afforestation, others
Underground storage	Enhanced oil recovery

The report describes approximately 80 to 90 GHG reduction technologies in 13 areas and various segments or sources within each area. Not all of the non-energy emitting areas are addressed by this study. It is estimated that over 95% of such emissions are covered in the scope of analysis. The definition of reduction technologies adopted for this study included abatement equipment, process modifications, product substitutions, trade-offs with GHG substances with lower global warming potential (GWP); and management practices. Carbon dioxide application markets, as well as reductions in consumption for products made from industrial processes emitting GHG were also in the scope of analysis. Two areas - biomass carbon sequestration and underground storage - which address both non-energy and energy emissions of carbon dioxide were also considered (as these did not come under the energy-related emissions category).

2.4 Methodology

The research methodology used to conduct this study involved a literature search, and direct contact of personnel from industry (producers, material and equipment suppliers, service providers), governments (Federal, Provincial, U.S. EPA, DOE), various research centres, associations, universities and other stakeholders with information related to the technologies and their development. The emphasis of the research methodology was on direct contact of personnel in the business system (all the above organizations). Approximately 205 interviews were conducted in Canada, the United States and - for some special technologies - Europe. The resources available for research and analysis for this study were limited to approximately three days of professional effort per segment, and less than one day per technology investigated. Therefore, detailed investigations of costs, market potential and development needs for each of the technologies could not be assessed. The consultant relied on industry and other stakeholder input to identify and select the most viable technologies to investigate.

The cost analysis for this project has the purpose of:

- identifying economic factors;
- providing an order-of-magnitude of total capital and operating expenditures;
- allowing a ranking of various technologies, based on unit costs;
- distinguishing areas that provide economic benefits from those that incur direct costs to reduce GHG emissions; and
- describing factors contributing to cost uncertainty that may require future research.

For most areas, costs were developed for only one or two of the technologies. Where possible, costs estimates available from literature sources were applied. In other cases, they were developed from available activity information and application of standard costs and prices gathered through industry contact and literature sources. The cost analysis is often based on simple models for adoption of a particular technology. Many simplifying assumptions have been applied.

While the study achieves the objectives for most of the areas and technologies, there are information gaps. In some cases, industry and specific emitting facilities have yet to formulate their approach or technologies to address reduction targets. Therefore, from a myriad of potential technology options, the implications of the potential requirement to reduce GHG emissions have yet to be considered.

2.5 Intended Use of this Report

This results of this study are not intended to serve as a prescriptive development strategy for technologies suitable for reducing GHG emissions from non-energy areas. Neither is there any intent to promote the technologies or any policies with respect to their implementation. Strategy and policy development by Environment Canada and other government departments will need to embrace a broader analysis of GHG emissions and solutions potentially involving trade-offs between energy and non-energy related emissions in each of the emitting sectors. Non-energy sectors may be able to reduce their GHG emissions more economically by dealing with energy-related emissions rather than applying technologies identified in this study dealing with the non-energy component of the problem. Furthermore, although direct costs for hypothetically adopting technologies are calculated, the results are not intended, and should not be viewed, as the total economic impact related to achieving reductions in each of the non-energy fields. Calculation of direct costs differ from economic impact analysis in many respects, including: direct costs are not projected into the future; and there is no evaluation of health environmental damages (solved or caused by adopting the technologies).

2.6 Acknowledgments

The consulting team wishes to express gratitude to the many individuals within corporations, governments, industry associations, universities and specialized research centres who provided information and insights on technologies related to addressing GHG emissions. In particular personnel at Environment Canada's, Pollution Data Branch who were responsible for preparing the 1995 GHG emissions inventory for Canada provided useful insights and assistance that allowed this work to carry forward efficiently.

3. Livestock: Enteric Fermentation

3.1 Summary

Ruminant (e.g., cattle, sheep) and non-ruminant (e.g., swine, horses) agricultural livestock generate methane emissions. In Canada, beef cattle represent the majority of such emissions, due to the size of the herd and the high emission rates per head (versus swine, horses, etc.). Poultry contribute negligible amounts of enteric methane emissions.

Domestic Livestock Population, Related Enteric GHG Emissions

	Population 1995	Total GHG Emissions	
	(million)	(Mt CO_2 -Eq)	
Beef cattle	12.4	33.7	78%
Dairy cattle	1.3	8.0	18%
Swine	11.9	1.1	3%
Sheep, goats	0.7	0.3	<1%
Horses, mules,	0.4	0.3	<1%
Poultry (all types)	116.1		
Total		43.4	100%

Technologies identified in this study which can reduce the amount of methane and carbon dioxide emitted from livestock include: greater use of feed additives (e.g., ionophores, antibiotics); steroid implants; improved livestock management and feeding practices; and bioengineering. All of these technologies and practices increase the production of milk or meat in relation to the amount of feed utilized or time taken.

Cost Summary for a 4.4% GHG Reduction

(Using Ionophores as Feed Additives)

	Amount of GHG Reduction (CH_4+CO_2)	Unit Cost For GHG Reduction
	kt	(\$/T-CO_2-eq)
Beef cattle (range feed low cost)	1625	\$20
Feedlot cattle (estimated)	0	0
Dairy (already on ionophores)	0	0
Dairy (rough estimate)[9] (not on ionophores)	245	(\$208)
Swine (ionophores not applicable)	0	0
Sheep, goats	18	\$55
Horses, mules, asses	16	(\$1000)
Total	1904	(\$18)
Percent of total GHG from livestock	4.4%	

Ionophores applied to livestock not already using the products can achieve close to a 4.4% reduction of GHG emissions from all livestock (includes methane and carbon dioxide). This technology needs to be combined with other technologies and managed under a holistic program to achieve greater GHG reduction levels that are measurable from this sector.

The results of the costing analysis infer the following conclusions which apply to ionophores as well as other technologies or practices:

- not all segments of the livestock population have equal cost and benefit structures associated with the various GHG reduction strategies;
- application of low cost additives (e.g., ionophores) can leverage savings in feed and yield benefits; and
- not all portions of the livestock population will be suitable to one solution (e.g., ionophores not suitable for swine).

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[9] Elanco, Personal Conversation.

3.2 Emissions and Trends

Ruminant (e.g., cattle, sheep) and non-ruminant (e.g., swine, horses) agricultural livestock generate methane emissions. Most of the methane is generated from ruminant animals, in which microbial metabolism of nutrients is the major source of the gas[10]. In Canada, beef cattle represent the majority of such emissions, due to the size of the herd population and the high emission rates per head (versus swine, horses, etc.). Poultry contribute negligible amounts of enteric methane emissions.

Domestic Livestock Population, Related Enteric GHG Emissions

	Population 1995	**Methane Emissions**	**Methane Emissions**	**Carbon Dioxide* Emissions**	**Total GHG Emissions**	
	(million)	(kt-CH_4)	(Mt CO_2 -Eq)	(Mt CO_2 -Eq)	(Mt CO_2 -Eq)	
Beef cattle	12.4	563	11.8	21.9	33.7	78%
Dairy cattle	1.3	133	2.8	5.2	8.0	18%
Swine	11.9	19	0.4	0.7	1.1	3%
Sheep, goats	0.7	5	0.1	0.2	0.3	<1%
Horses, mules,	0.4	5	0.1	0.2	0.3	<1%
Poultry (all types)	116.1	neg	neg			
Total		725	15.2	28.2	43.4	100%

Source: Jaques, et al[11].

Carbon dioxide emissions based on average of 5,756 litre/day/head for cattle[12]. Other animal emissions of CO_2 based on ratio of methane to carbon dioxide production for cattle.

* Carbon dioxide emissions are not reported with the "Livestock" category by Environment Canada. Emissions are believed to be inherently included in other categories and may be accounted for in land use or soil carbon flux models.

There were approximately 12.4 million beef cattle in Canada in 1995, with 3 to 4 million on feedlot or newborns. The remainder are on range feeding (which makes management more difficult and expensive). Many factors influence annual methane emissions from livestock, including temperature, diet, animal population, animal size, feed additives and livestock management practices.

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[10] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, Page, 49, April 1997.

[11] Ibid

[12] Kinsman, R., Sauer, F.,D., et al, "Methane and Carbon Dioxide Emissions From Dairy Cows in Full Lactation Monitored Over a Six-Month Period", Agriculture and Agri-Food Canada, Ottawa, 1995

3.2.1 Trends in GHG Emissions

In a conservative scenario, methane emissions from livestock will increase. Despite the fact that Canadian per capital consumption of beef (the main contributor to methane emissions) has been declining, the beef cattle population has remained relatively stable and could increase slightly driven by greater export sales. Per capita consumption of beef has declined in Canada over the last decade, dropping from 58.2 pounds in 1988 to 50.0 in 1996. This negative trend is likely to continue, as chicken continues to increase its domestic market share for meat consumption.

Trends in Canadian Meat Consumption

	Beef	Chicken	Pork	Turkey	Total
			(lb/capita)		
1988	58.2	48.3	46.7	9.5	162.7
1990	54.5	48.7	43.7	9.9	156.8
1995	50.5	54.7	46.3	9.7	161.2
1996	50.0	54.9	43.9	9.0	157.8

3.3 Technologies to Reduce Emissions

Technologies identified in this study which can reduce the amount of methane and carbon dioxide emitted from livestock include: greater use of feed additives (e.g., ionophores, antibiotics); steroid implants; improved livestock management and feeding practices; and bioengineering. All of these technologies and practices increase the production of milk or meat in relation to the amount of feed and other resources utilized.

Each of the technologies makes an incremental improvement in productivity and so achieves methane and carbon dioxide reductions. Some are already in place and are therefore serving to reduce GHG emissions. The portion of Canada's dairy and beef herds which already practice each of the technologies needs to be better defined to ensure overall reductions expected will in fact realized.

Examples of Cattle Methane Emission Reduction Options

Dairy Cattle	**Reductions Per Head**
Management practices that improve productivity	10 to 15%
Use of bST hormone to increase production	3 to 7%
Beef Cattle	
Management practices that improve productivity (improve cow-calf sector reproductive performance)	20 to 35%
Improve efficiency using ionophores	5 to 15%
Steroid implants on range cattle	<5%

Increasing production per unit of time or nutrient input decreases the amount of GHG (methane and carbon dioxide) emissions. Improved livestock management practices can increase livestock productivity, yielding more meat or milk per unit of methane released. The costs of applying various techniques are difficult to quantify, while the benefits can be significant. In some cases the costs provide immediate financial gain for producers - e.g., feed costs reductions. These may be offset by increased labour, land costs and materials.

A holistic approach combining such concepts as managed grazing; breeding, mechanical and chemical feed preparation, and lactation practices need to be adopted. For example intensive feeding, with proper paddock rotation can increase the efficiency of available feed resources and minimize the all inputs to output. Timing breeding practices to coincide with available feed reduces the requirements for additional feed. In this brief analysis a description of several technologies is provided.

3.3.1 Improved Cow-Calf Productivity

The cow-calf sector comprises a diverse set of operations varying in size, technological sophistication and resource availability. Cow-calf operations graze their cattle on pasture or rangelands, at least seasonally. Cattle allowed to graze over large areas, as is likely to be the case in western Canada, are more difficult to manage. Approximately 70% of the total cattle population is located in the provinces of Alberta, Saskatchewan and Manitoba. Animals fenced in smaller pastures or corrals, as is more likely to be the case in eastern Canada, can be more effectively managed. Therefore the ability to manage the herds to increase productivity, at the same time achieving GHG emission reductions will vary depending on the region and interest of cattle owners.

In general cow-calf operators try to maximize the number of calves born per unit of time as well as per cow. Typically, cows can produce about 8 calves during a normal lifetime. Non-productive cows lower the efficiency of the operations and contribute to higher levels of methane emissions per unit of final product. Well managed operations enable cows to calve at 24 months of age.[13] Even a one year delay would imply a 1/8th or 13% reduction in efficiency.

It is also important to manage the number of calves weaned per 100 cows mated each year. Cows that do not wean a calf consume feed (as well as other resources such as labour) without yielding product. Approximately 80 to 85% of the cows mated in a year should be able to wean a calf under normal circumstances.[14]

There are many management options to increase the productivity of cow-calf operations. Optimal combinations of various practices are specific to owners, and the mix and costs of resources such as feed type, labour, and facilities available. Animal nutrition programs can be applied to some degree by all owners to achieve increases in productivity and reductions in methane emissions.

Nutrition related problems contribute to low pregnancy rates (therefore low weaning percentages), and difficulty in getting cows to calve at 24 months. In forage based production programs (as may be the case in many western Canadian operations), producers can improve nutritional management by:[15]

- assessing soil conditions (through proper testing) to determine fertilizer requirements for their forage;
- assessing forage quality to determine supplementary nutrients (minerals, proteins, etc.) required; and
- eliminating toxic plants that can influence animal productivity.

It is estimated that these and other management techniques (such as artificial insemination to ensure high pregnancy rates, veterinary care, vaccinations) can theoretically increase productivity by 20 to 35%, and achieve similar reductions in GHG emissions. This level of reduction assumes these practices are not currently employed. In Canada, actual increases in productivity and reductions in GHG emissions is likely to be less, given the assumption that the industry employs some of these management tools.

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[13] Opportunities to Reduce Methane Emissions in the United States - Report to Congress, USEPA, EPA 430-R-93-012, Oct. 1993

[14] Ibid

[15] Ibid

3.3.2 Ionophores

Ionophores are complex molecules which can modify the movement of ions across biological membranes and can therefore affect the metabolism of various microbes. In the rumen of livestock, ionophores can result in selectively promoting the growth of certain bacteria over others. The metabolism of the favoured bacteria can affect the host animal to provide a nutritional or metabolic advantage over a non-supplemented animal.[16]

Ionophores are incorporated in ruminant animal feeds to increase the feed-efficiency (production per unit of nutrient), as well as assist in control of diseases. Furthermore, the additive can facilitate the use of lower quality feeds (i.e., with a lower nitrogen content).

It is estimated that 30 to 40% of the total Canadian cattle population already use ionophores. Over 90% of the beef cattle that are in feedlots use ionophores. However, beef cattle that are range grazing are not typically using ionophores.

Industry suppliers of ionophores estimate 50% of dairy cattle use this feed additive. Although these additives are not registered for use in dairy cattle, "off-label use" or use under veterinary prescription does occur. Industry suppliers claim ionophores are used to minimize the occurrence of various diseases and to increase productivity. Bulls are raised for their reproductive capabilities rather than meat consumption and therefore do not have a requirement for feed-efficiency enhancing ionophores.

Ionophores are not used in swine (since swine do not have rumens) and only a minor portion of the sheep, lamb and goat populations may use the product. According to industry suppliers, practically 100% of the domestic poultry population are on various ionophores or comparable feed additives. For poultry, ionophores play a key role in controlling disease, especially coccidiosis.

Ionophores can reduce methane emissions, although the exact amount per head is difficult to quantity and dependent on many factors. One Canadian researcher claims reductions of 8 to 10% were observed upon initial ionophore treatment.[17] Ionophores act in two ways to reduce emissions of methane and carbon dioxide. One contribution is to increase the efficiency of feed utilization and therefore overall productivity. Livestock on ionophores can produce more product (i.e., milk, meat) faster and with less feed. This results in a lower amount of methane or carbon emissions per unit of production.

The amount of methane and carbon dioxide reduction is difficult to quantify and research continues to better understand the interrelationships of various factors. Factors that influence the

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[16] Bagg, R., Mode of Action of Ionophores in Lactating Dairy Cattle, Elanco Animal Health, Guelph, ON.

[17] Personal conversation Frank D. Sauer, Agriculture Canada, January 12, 1998.

generation of GHG emissions with respect to the use of ionophores include: type and quality of the feed; ratios of energy and fibre intake; digestive tract physiology; metabolism; age; sex; and the activity level of the animal.[18]

Also affecting GHG production from some animals may be the duration of the ionophore treatment. In one study[19] of lactating cows, ionophores "significantly decreased" (8 to 10%) methane emissions while having little effect on carbon dioxide emissions. There were other observed effects, namely: a significant decrease in dry matter intake; increased milk production; and reduction in the percentage of milk fat. According to the study, ionophores also impact the milk fatty acid profile, reducing saturated fat and increasing unsaturated fat. The study points out that conjugated dienes which have been the subject of attention due to evidence indicating their effectiveness as anticarcinogenic agents, where also increased, thereby increasing the nutritional value of milk.

However, approximately 5 months after the withdrawal of the ionophores a reintroduction resulted in a slight, but "insignificant decline" in methane emissions. There were also effects in relation to feed intake, milk production and milk fat profile. The conclusion is that more research on the effects of ionophores is required to analyze potential microbial resistance to the ionophores, investigate the optimal period of exposure and the implications of ionophore rotation in increasing the effectiveness of similar feed additives.

3.3.2.1 Ionophores Suppliers

Suppliers of ionophores in Canada are a subset of companies from the global pharmaceuticals industry. Canadian suppliers typically import active ingredients for domestic distribution. This study identified five suppliers of ionophores (or very similar products) licensed for use in livestock.

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[18] Agriculture and Agri-Food Canada, Centre for Food and Animal Research (CFAR), Greenhouse Gas Emissions Research Project.

[19] Fellner, V., Sauer, F.D., Kinsman , R., and Kramer, J.K.G., The Effects of Rumensin® on Milk Fatty Acid Profiles and Methane Production in Lactating Dairy Cows, Agriculture and Agri-Food Canada, Centre for Food and Animal Research (CFAR), 1997

Identified Suppliers of Ionophores and Other Feed Additives

Company	Location	
Elanco (Eli Lilly Canada Inc.)	Toronto	ON
Hoechst Canada Inc.	Montreal	PQ
Hoffmann-LaRoche Ltd.	Cambridge	ON
Pfizer Canada Inc.	Point Claire	PQ
The Upjohn Company of Canada	Toronto	ON

The broader pharmaceuticals industry in Canada consists of approximately 140 pharmaceutical establishments, mostly (80%) concentrated in Ontario and Quebec. Approximately 20 or so companies capture 80% of the market. Most companies are small formulators having only one or two product lines and relatively short production runs. No company has more than 7% share of the total market, since there are usually several competing products in each therapeutic segment. (Industry Canada).

3.3.3 Hormones and Steroids

Bovine somatotropin (bST) is a naturally occurring growth hormone found in cattle. Over the last couple of decades, the ability to synthesize the hormone using recombinant DNA techniques has increased the availability of the product and lowered its price. Studies indicate that bST injections in lactating dairy cows can increase milk production and lower methane emissions by nearly 10%[20]. However, concerns have been raised regarding the use of bST to enhance milk production, especially hormone derived from recombinant DNA production techniques. (It could not be confirmed in time for completion of this report whether bST is approved for use in dairy cattle in Canada.)

Anabolic steroids are effective in increasing the rate of weight gain and improving feed conversion in beef cattle. These effects are achieved by directing the energy used to deposit fat in the animal to the deposition of protein. Anabolic steroids produce leaner beef at slaughter. There are numerous steroids that have been approved for cattle including, progesterone, testosterone, zeranol, estradiol and trenbolone. Each of these different products are used in varying degrees among steers, heifers, and males grown for beef. Since these products act in similar ways to pharmaceuticals, Health Canada is responsible for product approvals.

Small pellets of steroids are often implanted under the skin of the animal's ear. The implants will increase the rate of weight gain by 10 to 15% and improve the feed efficiency by 5 to 10%[21]. As

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[20] Opportunities to Reduce Methane Emissions in the United States - Report to Congress, USEPA, EPA 430-R-93-012, Oct. 1993

[21] Ibid

a result, animals generate less methane over their lifetime. A large portion (as high as 80%) of feedlot beef cattle, especially in Western Canada, are already on steroids. The portion of range cattle or cattle on small farms on steroids is not well defined, although it is estimated to be substantially lower.

3.3.4 Bioengineering

Bioengineering involves application of biotechnology to develop livestock with greater product yield per unit of nutrients consumed. There are various potential biotechnology innovations which increase yield while reducing methane emissions. These include twinning, rumen microbe manipulation and hormones manipulation, to mention some. These practices have not been broadly adopted in Canada.

3.3.4.1 Twinning

Twinning reduces the number of cows required to produce a given number of calves. There are several strategies for improving productivity through twin births. One technique is to inhibit the hormone that suppresses twinning. Twinning can be practiced as part of a broader feed/livestock management system. For example, if excellent pasture conditions are expected in the coming season, twinning can be promoted due to the availability of nutrition. If poor conditions are expected single births may be preferred. Better predictions of the future forage conditions than are currently available may be necessary to leverage the benefits of twinning. Another management option is to improve the nutrition of cows carrying twins to reduce the rate of stillbirths. Considering the close management (monitoring) that is required to realize the benefits of twinning, few cattle producers are involved in the practice. Farms with large range herds are not likely to undertake the practice.

3.3.4.2 Bioengineering Rumen Microbes

Methane is generated by microbes in the rumen. It is theoretically possible to bioengineer or "select" microbes that improve the feed utilization, thereby reducing the amount of methane produced. Research is required to better define the parameters associated with this technology. For example, there is a requirement to determine the key methanogenic species and their activity under different diets.

3.3.4.3 Transgenic Manipulation

Transgenic manipulation involves developing superior genomes through the manipulation of genetic material using recombinant DNA, embryo manipulation and embryo transfer techniques[22]. To date efforts in this field have involved promoting expression of growth hormones, as has been successful in other species, such as mice. The benefit of this approach is that the genetic material can be transferred to future generations.

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[22] Ibid.

3.4 R&D Capabilities and Requirements

Canadian universities and other research centres which specialize in the agriculture sector, conduct some research on GHG emissions from livestock. Agriculture and Agri-Food Canada (AAFC) also plays a major role, with R&D facilities spread out across Canada.

An example of research related to GHG had been undertaken by Agriculture and Agri-Food Canada's, Centre for Food and Animal Research (CFAR). Their five year research program, started in 1992 with the objectives of: reducing the uncertainty concerning the contribution of farm animals to GHG emissions; evaluating the effectiveness of existing techniques for reducing methane gas emissions from farm animals housed in typical farm building; and developing new ways of reducing such emissions. Technologies researched by the group include: in-barn management practices (lighting schedules; milking timetables, etc.); effect of ionophores and other additives to reduce gas emissions; and the introduction of methane oxidizing bacteria in the rumen of the animals. The program was recently shut down. Its facilities were closed and scientists involved in the program have disbanded.

Agriculture and Agri-Food Canada's Major Animal Research & Development Centres

Location	Province	Emphasis
Lennoxville	Quebec	Dairy cattle, Swine
Lethbridge	Alberta	Crops, beef cattle
Summerland	British Columbia	Poultry
Lacombe	Alberta	Other animals
Fredericton	New Brunswick	Dairy (recent changes - may not be operating)

The University of Alberta has capabilities in the beef cattle industry. The University of Guelph has a strong international reputation related to food and agriculture education and research. McGill University has capabilities in the dairy industry. These and other facilities work collaboratively with AAFC, each other and institutions in other countries.

Institutions Specializing in Agriculture and Livestock Research

(with respect to GHG Emissions)

Canadian	**Livestock Focus**
University of Alberta	Beef cattle
McGill University	Dairy cattle
Agriculture and Agri-Food Canada, Centre for Food and Animal Research (CFAR) (Recently Closed)	Dairy
University of Guelph	Swine
United States Universities	
Utah State	Range management
Purdue	Dairy
Iowa State	Swine
Cornell	Dairy
Nebraska	Beef

Pharmaceutical manufacturers are divided into two basic groups: patent-holding ("innovative") firms and generic firms. Patent holding firms have about 63% of the volume of Canadian drug sales but 87% of the revenues (due to higher prices). They are usually branches of multinational companies which have been granted patent protection for their drugs for a period of up to 20 years. In 1986, the multinational firms were granted increased intellectual property protection in return for a pledge to increase spending on domestic research and development. The amount of R&D spending in Canada has increased to reach an R&D-to-sales ratio of over 10% in the early 1990's, from a level of about 5% in 1986. In 1993, legislation was passed (C-22) to bring the level of patent protection of pharmaceuticals to 20 years, in line with international standards.

Basic research activities for ionophore suppliers is typically carried out near head-office locations in the United States and Europe. Some R&D activity related to product registration may be carried out domestically. Elanco claims to spend the most of any firm in this field with annual R&D expenditures of close to $1 million.

3.5 GHG Reduction Costs

Reduction in GHG emissions from livestock can be achieved through application of a variety of technologies and management practices, including use of feed additives, better cow-calf sector practices, steroids, and bioengineering. Rather than attempt to cost all the options available, a brief economic analysis for one technology is provided as an indication of the cost factors, impact of the direct benefits, and the levels of GHG reductions possible. Using ionophores as a case study, the cost estimates for reducing GHG emissions from enteric fermentation in agricultural livestock is based on the following model:

1. ionophores dosage rate is increased over current level;
2. ionophores incorporated into feeds of livestock not already using (dairy cows, cattle on range feeding);
3. ionophores achieve a 15% reduction per animal;

Costs not included in this analysis are: registration costs to obtain approvals for increased dosage levels; and costs to register ionophores usage among animals not currently approved. These can be very high and may take a long time.

Direct benefits that may result from the increase use of ionophores include: increased yield; lower feed costs; and less disease.

The daily cost of ionophores is very approximately 2.5¢ per day per head[23]. To achieve greater reductions in methane emissions, the ionophore dosage may need to be increased to 2 to 3 kg/1000 kg of feed[24].

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[23] Dr. Gary Mathieson, Personal conversation.

[24] Elanco, Personal Conversation.

Estimated Costs and Benefits to Reduce GHG Emission Using Feed Additives (Ionophores)

	Livestock Population	Portion of Population Adopting Technology	Annual Cost of Using Ionophores (@2.5¢/day)	Daily Cost of Feed[25]	Feed Savings	Net Costs of Using Ionophores	Amount of GHG Reduction (CH_4+CO_2)	Unit Cost For GHG Reduction
	(million head)		($million)	(¢/day)	($million)	($million)	kt	($/T-$CO_2$-eq)
Beef cattle (range feed low cost)	8.9	100%	$81	10	$49	$32	1625	$20
Feedlot cattle (estimated)	3.5	0%	0	150	0	0	0	0
Dairy(rough estimate)[26] (already on ionophores)	0.7	0%	0	140	0	0	0	0
Dairy (rough estimate) (not on ionophores)	0.7	100%	$6	160	$57	($51)	245	($208)
Swine (ionophores not applicable)	11.9	0%	0	15	0	0	0	0
Sheep, goats	0.7	100%	$7	15	$6	$1	18	$55
Horses, mules, asses	0.4	100%	$3	100	$19	($16)	16	($1000)
Total	26.8		$97		$131	($34)	1904	($18)

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[25] Dr. Gary Mathieson, Personal conversation.

[26] Elanco, Personal Conversation.

The results of the costing analysis point out the following:

- not all segments of the livestock population have equal cost and benefit structures associated with the various GHG reduction strategies;
- application of low cost additives (e.g., ionophores) can leverage savings in feed (or provide yield benefits); and
- not all portions of the livestock population will be suitable to one solution (e.g., ionophores not suitable for swine).

Ionophores applied to livestock not already using the products can achieve close to a 4.4% reduction in GHG emissions from all livestock (includes methane and carbon dioxide). This technology needs to be combined with other technologies to achieve greater GHG reduction levels from this sector.

3.6 Recommendations

To achieve GHG reductions from livestock, a broad management approach is required that takes into consideration the many stakeholders, including the producers. In the United States, the Environmental Protection Agency (EPA) has established a livestock GHG "champion" to coordinate the major components of such a program.

Any management system requires a clear identification and segmentation of the problem, some benchmarking of key manageable parameters and monitoring of progress. In this areas, research may be oriented to better understand the role feed additives, management practices and bioengineering currently play and can play in the future to reduce GHG emissions from livestock. A major limitation in this area is the lack of quantitative information required to link more closely the changes in the beef and dairy production and marketing systems to the changes in production practices that can reduce methane emissions[27]. A greater level of analysis is required to establish a GHG management system, which may first require a better understanding of producers, their practices and the approaches which can be used to monitor progress, if some the technologies are adopted. Agriculture and Agri-food Canada has already established some programs related specifically to GHG emissions. This has included some benchmarking activity. However, recent reductions in financial resources available, closure and restructuring of some research centres, elimination of some programs have altered the Department's R&D activities related to this field and requirements for the future.

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[27] Opportunities to Reduce Methane Emissions in the United States - Report to Congress, USEPA, EPA 430-R-93-012, Oct. 1993

Some of the specific areas that may require more R&D emphasis to achieve GHG reductions include:

- analysis to benchmark and monitor practices with respect to GHG emissions;
- rotation on different ionophores to minimize adaptation by cattle;
- GHG reduction potential for range cattle;
- additives and nutrients in context of improving livestock management practices; and
- bioengineering.

Canadian involvement in this area may be considered as part of a global system of cooperation. The United States EPA, for example, has promoted programs to improve livestock production efficiency while addressing GHG emissions. Canada should adopt an international perspective in dealing with livestock emissions. Working with other nations may achieve greater benefits versus domestic efforts. For example, India has 277 million cows and very low per capita beef consumption[28]. However, solutions applicable in Canada are not likely to be the same as those in other countries.

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[28] Canfax Research, Calgary, AB, Statistical Briefing, Sept. 1997.

4. Livestock: Manure

4.1 Summary

The majority of the research to date on technologies to reduce methane (CH_4) emissions from livestock manure has centered on anaerobic digesters. Approximately a decade ago, 10-15 anaerobic digesters were installed at Canadian farms. However, they all failed due to the fact that: (i) the program promoting these digesters was canceled eliminating technical support for the farmers; (ii) many of the digesters broke down after a short period; and (iii) the cold climate in Canada reduced the economic feasibility of the digesters. Currently, there are no known anaerobic digesters operating at Canadian farms. However, digesters have become much more efficient and technologically advanced over the last decade.

Most of the current research in Canada in this area is centered on aerobic composting systems which transfrom the manure into a marketable fertilizer. There are approximaltey 10 Canadian companies that are at various stages in the commercialization of this technology. A few of these companies are at the demonstration stage and expect to be selling systems within one year. Canada is at the forefront in North America in developing these systems as many U.S. farms have made inquiries to the Canadian technology developers.

As more robust cost data are available for anaerobic digesters, the economics have focused on that technology. Shown below is a case study to determine the cost per tonne of CO_2 equivalent reduced from the use of anaerobic digesters. Data for this example was derived from case studies provided by the EPA. The sample farm has a total of 350 dairy cows which results in a total of 12 tonnes of methane emissions (i.e., 252 tonnes of CO_2 equivalent) annually if uncontrolled. A plug-flow digester is assumed to be installed.

Case Study on Cost per Tonne of CO_2 Equivalent Removed by Installing a Plug-Flow Digester

	Cost/Benefits	$/ tonne
Capital Cost	$270,000	
Annualized Capital Cost	$30,000	
Annual Operating Cost	$29,000	
Gross Total Annual Costs	$59,000	$426
Annual Energy Benefits	$58,000	$422
Net Cost per Tonne of CO_2 Reduced*		$4
Estimated CH_4 Reduction	50%	
Estimated CO_2 Equivalent Reduction	140 tonnes	

* Large possible range (e.g., net benefit to net cost of $20/tonne)

Additional environmental benefits, not outlined in the above table, are realized from the use of anaerobic digesters. Biogas generated from anaerobic digesters is used to offset electricity demand which in turn may reduce the amount of CO_2 that is emitted if fossil fuels are used for electricity generation. Taking this benefit into consideration is beyond the scope of this study.

It has been shown that when anaerobic digesters are introduced at farms that have been emitting large amounts of CH_4, emissions have been reduced by up to 70-80%. In the above table, the CO_2 emissions that would result from combustion of the biogas have been entered into the calculation. This is the rationale behind the 50% reduction in CH_4 that is outlined in the above table, instead of the 70-80% that is reported by the EPA. However, keep in mind that the CO_2 reductions from reduced fossil fuel demand have not been taken into consideration.

Manure management systems that store manure under anaerobic conditions contribute about 60% of the CH_4 from this source because CH_4 is produced during anaerobic decomposition of organic materials in manure. Analysis by US EPA suggests that farms with 300 dairy cows or 2,000 pigs would be viable candidates for anaerobic digesters. (The EPA has also indicated that smaller farms can also be viable candidates depending on certain factors. It should also be noted that of the current anaerobic digesters operating in the U.S., several have far less livestock than is recommended by the EPA).

Large Livestock Farms in Canada

Province	Farms with Between 100 and 300 Dairy Cows	Farms with >300 Dairy Cows	Farms with Between 1,000 and 2,000 Pigs	Farms with >2,000 Pigs
Newfoundland	14	0	1	0
Prince Edward Island	10	0	21	10
Nova Scotia	32	2	22	16
New Brunswick	20	1	25	5
Quebec	211	3	760	366
Ontario	303	8	517	217
Manitoba	69	3	160	213
Saskatchewan	47	1	66	85
Alberta	219	5	254	206
British Columbia	209	5	29	27
Canada	**1,134**	**28**	**1,855**	**1,145**

Source: Statistics Canada

The AgSTAR program (EPA's manure management program) estimates that over 2,000 livestock facilities across the U.S. could install cost effective biogas recovery systems. In Canada, there are 28 reported farms with more than 300 dairy cows and 1,145 farms with more than 2,000 pigs. However, some of the smaller farms (i.e., the 1,134 Canadian farms with between 100 and 300 dairy cows as well as the 1,855 Canadian farms with between 1,000 and 2,000 pigs) may also be viable candidates. It is unclear if feed lots which house a large number of beef cattle could also be viable candidates for anaerobic digesters. Most, if not all, digesters operating in the U.S. are located at dairy or pig farms. Several European poultry farms have anaerobic digesters.

Total Cost to Reduce CH_4 Emissions with Anaerobic Digesters

Total Dairy Cow and Pig Manure CH_4 Emissions	121 kt
Assumption - Large Farms Represent 60% of Total CH_4 Emissions	60%
Large Dairy Cow and Pig Farm CH_4 Emissions	72 kt
Estimated CH_4 Emission Reduction with Anaerobic Digesters	50%
CH_4 Reduced at Large Farms with Anaerobic Digesters	36 kt
Percentage Reduced From Total CH_4 Dairy Cow and Pig Manure Emissions	30%
Equivalent CO_2 Reduction	750 kt
Total Gross Capital Cost to Canada	$615 million
Annualized Gross Total Cost (per tonne of CO_2 reduced)	$426
Net Cost Per Tonne of CO_2 Reduced*	$4
Total Net Cost to Canada *	$4 million/yr

* Incorporated energy benefits from either on-farm use of energy produced or sale to electrical grid.
This calculation assumes all large farms in Canada install an aerobic digester.
Note: Large farms are assumed to have over 100 dairy cows and over 1,000 pigs.

Some of the current R&D work in Canada is not focused on digesters but instead on other technologies that can reduce CH_4 emissions from livestock manure. For instance, Agriculture and Agri-Food Canada is currently funding research on aerobic composting of hog manure as well as bioreactors that reduce CH_4 emissions from manure. Both of these technologies, while not implemented at actual farms yet, are promising as cost effective tools to reduce CH_4 emissions from livestock manure.

4.2 Background

Unlike many of the other sections in this report, there is no formal industry structure to review in terms of where GHG emissions emanate from and where mitigating technologies can potentially be implemented. Livestock farms are located throughout the country and range from small hobby farms to large complex farms with thousands of livestock.

1995 Canadian Inventory of Livestock

	Number of Animals (1,000)
Cattle - Beef	12,448
Cattle - Dairy	1,271
Goats	22
Sheep	717
Pigs	11,939
Horses/Mules/Asses	356
Poultry	116,113
Total	**142,865**

Source: Environment Canada, *Trends in Canada's Greenhouse Gas Emissions 1990-1995.*

As mentioned, to utilize some of the technologies that have been developed to reduce CH_4 emissions from livestock manure, the U.S. EPA has estimated that livestock facilities should have at least 300 head of dairy cows/steers or 2,000 swine in confinement, where nearly 100% of the manure is collected regularly.

It should be noted that smaller confined facilities could potentially support successful recovery projects, given site-specific and market conditions. Livestock facilities that have little variation in the daily confined animal populations (i.e., have predictable manure production which will ensure that a consistent amount of manure is available for collection year-round) are also potential candidates.

However, as will be pointed out in this chapter, it is the large farms that contribute a significant portion of the annual CH_4 emissions from livestock manure due to the specific manure management systems they have in place. Therefore, it is these farms that can significantly reduce CH_4 emissions if they implement the currently available and future technologies.

4.3 Emissions and Trends

Waste from livestock is primarily composed of water and organic material. The component of organic material that can be decomposed by microorganisms is the volatile portion, referred to as volatile solids. Under specific conditions, a portion of the volatile solids can be converted to methane.[29]

Livestock waste decomposition can occur either aerobically or anaerobically. Under aerobic conditions, organic material in the livestock waste is decomposed by aerobic and facultative bacteria using molecular oxygen. The end products of aerobic decomposition are CO_2 and stabilized organic material. Under anaerobic conditions, the organic material in livestock waste is decomposed by anaerobic and facultative bacteria. End products of anaerobic decomposition are CH_4, CO_2, and stabilized organic material. Bacteria responsible for CH_4 production in animal waste are strictly anaerobic.

Livestock waste composition determines the maximum CH_4 producing capacity. In turn, composition of livestock waste is determined for the most part by what the animal consumes. For instance, high energy content and digestibility of feed results in a greater CH_4 producing capacity of the waste. Waste from cattle fed a high energy corn-based diet will produce about twice as much methane as the waste of cattle fed a roughage diet.[30]

Two factors that influence the amount of CH_4 produced from livestock manure are: (i) the characteristics of the animal waste management system; and (ii) climate. Characteristics of the waste management system that influence CH_4 production are:

- contact with oxygen - under aerobic conditions where oxygen is in contact with the waste, there is no potential for methane production;
- moisture content - liquid based systems promote an oxygen-free environment and anaerobic decomposition. Moist conditions increase the potential for CH_4 production;
- pH - methane producing bacteria are sensitive to changes in pH. The optimal pH is near 7.0 but CH_4 will be produced in a range between 6.6 and 7.6. Changes in pH from 7.0 will decrease the rate of CH_4 production; and
- nutrients - bacterial growth depends on the availability of nutrients such as nitrogen, phosphorous and sulphur. Deficiency in one or more of these nutrients will inhibit bacterial growth and methane formation.

Manure management systems which utilize anaerobic conditions cause the most CH_4 emissions. These systems include liquid/slurry storage systems, pit storage systems, and anaerobic lagoons.

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[29] US EPA, Options for Reducing Methane Emission Internationally - Volume II: International Opportunities for Reducing Methane Emissions - Report to Congress, October 1993, pg. 6-2.

[30] Ibid.

A small percentage of livestock manure worldwide is managed with these systems. However, it has been estimated that these types of systems are responsible for about 60% of global livestock manure CH_4 emissions. Manure management systems which involve contact of the manure with air (e.g., uncollected on the range or spread directly on the crops or pastureland) have small CH_4 production potential.[31]

With respect to climatic conditions, the factors that influence CH_4 production are:

- temperature - CH_4 production generally increases with rising temperature; and
- moisture - moisture content of the livestock waste determines the rate of bacterial growth and waste decomposition. Moist conditions promote CH_4 production.[32]

1995 Canadian CH_4 Emissions from Livestock Manure

	Number of Animals (1,000)	**Emission Estimates (kt CH_4)**	**Aggregate Emission Factor (kg CH_4 per animal)**
Cattle - Beef	12,448	135	10.8
Cattle - Dairy	1,271	44	34.4
Goats	22	nil	0.0
Sheep	717	4	5.1
Pigs	11,939	77	6.4
Horses/Mules/Asses	356	nil	0.0
Buffalo			
Camels and Llamas			
Poultry	116,113	12	0.1
Other			
Total	**142,865**	**271**	**1.9**

Source: Environment Canada, *Trends in Canada's Greenhouse Gas Emissions 1990-1995.*

The Canadian trend in CH_4 emissions from livestock manure over 1990-1995 is tied directly to animal populations. During that period, only Ontario and the Atlantic provinces have shown a decline in cattle populations. An overall increase of 15% in livestock populations has been observed nationally from 1990-1995, causing a net increase of about 12% in CH_4 emission over the period.[33]

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[31] Ibid.

[32] U.S. EPA, Global Methane Emissions from Livestock and Poultry Manure, February 1992, pg. 11-15.

[33] Environment Canada, "Trends in Canada's Greenhouse Gas Emissions 1990-1995", April 1997, pg. 51.

4.4 Technologies to Reduce Emissions

Most of the research to date to reduce CH_4 emissions from livestock manure has been focused on anaerobic digesters to collect the biogas that results from the microorganism decomposition of manure. Biogas technology is a manure management tool that recovers and uses methane as energy source. Collected biogas can then: be used as a fuel source to generate electricity for use on the farm; be sold to the electrical grid; or be used for heating or cooling needs.[34]

Animal Waste System Usage in North America

Animal	Anaerobic Lagoons	Liquid Systems[1]	Daily Spread	Solid Storage & Drylot	Pasture, Range & Paddock	Used for Fuel[2]	Other Systems[3]
Non-Dairy Cattle[4]	0%	1%	0%	14%	84%	0%	1%
Dairy	10%	23%	37%	23%	0%	0%	7%
Poultry[5]	5%	4%	0%	0%	1%	0%	90%
Sheep	0%	0%	0%	2%	88%	0%	10%
Swine	25%	50%	0%	18%	0%	0%	6%
Other Animals[6]	0%	0%	0%	0%	92%	0%	8%

Source: US EPA, *Global Methane Emissions From Livestock and Poultry Manure*, February 1992.

[1] Includes liquid/slurry storage and pit storage

[2] Includes anaerobic digesters and burned for fuel

[3] Includes deep pit stacks, litter, and other

[4] Includes buffalo

[5] Includes chickens, turkeys, and ducks.

[6] Includes goats, horses, mules, donkeys, and camels.

The largest potential to reduce CH_4 emissions are at farms where manure is managed anaerobically in liquid or slurry form or stored over time as a solid. Work by the EPA has revealed that significant opportunities exist to reduce CH_4 emissions in North America, due to the fact that:

- livestock in this area are usually managed in confined areas, with some method for collecting and managing the resultant concentrated quantities of manure in place; and
- much of the manure in North America is either handled in liquid systems (25 to 75% of many types of manure) or stored as a solid (e.g., in North America about 33% of manure from dairy cattle and 75% of swine manure is handled in liquid systems).

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[34] U.S. EPA, AgSTAR Handbook, A Manual for Developing Biogas Systems at Commercial Farms in the United States, July 1997, pg. 1-1.

Although technologies for methane recovery are available, only small amounts of methane are currently recovered for use (i.e., only a few farms in North America are using anaerobic digesters).[35]

Anaerobic digesters provide significant ancillary benefits in addition to reducing CH_4 emissions, such as:

- recovered CH_4 from livestock manure can be used to generate electricity for sale or use on the farm;
- slurry remaining after digestion can be utilized as livestock feed, an aquacultural supplement, or fertilizer;
- reduction in ground and surface water contamination or eutrophication from manure runoff;
- reduction in the spread of pathogens and diseases; and
- virtual elimination of odours from livestock manure.[36]

Recovered biogas is 60-80% methane, with a heating value of approximately 600-800 Btu/ft^3. This high quality gas can be: used to generate electricity; used as fuel for a boiler, space heater, or refrigeration equipment; or combusted as a cooking and lighting fuel. Most equipment that uses natural gas, propane, or butane for fuel can use biogas. Electricity generated from biogas could also be sold to the local electricity power grid.

The use of antibiotics (or ionophores) in the feed given to animals is not synergistic with manure methane generations. Antibiotics kill the organisms that produce the methane in digesters. This has implications on potential mitigation options for ruminant animals.

Technologies identified and reviewed in this section are:

- anaerobic digesters;
    - covered lagoons;
    - large scale digesters;
    - small scale digesters;
    - slurry digesters;
    - mesophilic digesters; and
    - other types of digesters.
- constructed wetlands;
- aerobic composting; and
- bioreactors.

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[35] US EPA, Options for Reducing Methane Emission Internationally - Volume II: International Opportunities for Reducing Methane Emissions - Report to Congress, October 1993, pg. 6-6.

[36] Ibid, pg. 6-8.

4.4.1 Covered Lagoons

Covered lagoon digesters are suitable for large-scale, intensive farm operations that are common in North America, Europe, and regions of Asia and Australia. These digesters have the potential to capture a large portion of the CH_4 produced from anaerobic waste fermentation. However, a practical estimate is that 40% of the CH_4 could be mitigated.

Covered lagoon digesters are most applicable to dairy and swine operations using liquid manure management systems. The total solids concentration in the influent should be less than 2%. These digesters operate most efficiently in temperate to warm climates where the ambient lagoon temperature is high enough to sustain continuous biogas production (covered lagoons may be used in cold climates for seasonal biogas recovery and odour control).[37] The U.S. EPA estimates that up to 3,000 dairy and swine farms in the U.S. may profit from methane recovery technologies like covered lagoons.[38]

Covered lagoon digesters contain a floating impermeable cover placed over the surface of a manure treatment/storage lagoon. Biogas from the decomposing manure is collected under the cover. Covered lagoon digesters have been shown to be quite applicable to flush swine and dairy operations. At these operations, recycled water flushes the manure from the confinement facilities. Water and manure then run into the primary lagoon (through a solids separator at dairy operations) which has a large cover made of durable membrane. Under this cover, microorganisms work to break down the manure and produce biogas, which is about 70% CH_4 and 30% CO_2. The biogas bubbles to the surface and is caputred under the cover. The gas is then piped out and used to generate electricity, heat water, and even to run chillers.[39]

Covered lagoons are the simplest type of methane recovery system. These digesters consist of two engineered holes in the ground, one of which is topped with a gas-tight cover. Additional components to the system include methane utilization equipment, a solids separator (at dairies), and an optional heat exchanger. [40]

One of the primary benefits of covered lagoon digesters is that they can produce significant quantities of methane gas which may be used as an on-farm energy source (i.e., farmers can reduce electric, gas and oil bills). Covered lagoons can increase farm revenues from the sale of manure by-products such as soil additives and compost enhancers. They can also improve recycled flush-water quality; reduce unpleasant odour and help minimize the chances for contamination of surface and ground water.[41]

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[37] U.S. EPA, AgSTAR Handbook, A Manual for Developing Biogas Systems at Commercial Farms in the United States, July 1997, pg. 1-2.

[38] U.S. EPA, AgSTAR Technical Series: Covered Lagoon Digesters, pg. 1-2.

[39] Ibid.

[40] Ibid.

[41] Ibid.

Costs of covered lagoon systems vary based upon the size and location of the farm. For instance, the current manure management system dictates what additional components must be designed and installed to create a complete system. There are four major capital costs components associated with installing a covered lagoon digester system:

- the cost of the cover represents the most significant capital cost for covered lagoon digesters. This cost varies depending upon the lagoon size and the cover material. In general, a lagoon cover costs approximately $2.50/square foot;
- cost of an engine generator depends on its size and whether or not it includes heat recovery. A generator costs about $870 per kW without a heat exchanger and $1,500 per kW with a heat exchanger;
- excavating a new primary lagoon costs approximately $2.50/cubic yard; and
- the cost of designing the methane recovery facility and managing construction and start-up. This cost is fairly standard and runs about $35,000 per project. [42]

Operating costs for repairs and maintenance of the methane recovery facility are about $0.022 per kWh of electricity produced.

Economics for Actual Covered Lagoon Digesters in the U.S. (C$)

Farm Description	**1,000 Milker Dairy**	**150 Milker Dairy**	**300 sow farrow-to-feeder**	**1,650 sow farrow-to-finish**
Total Capital Costs	$370,000	$64,000	$23,000	$320,000
Annual Electricity Benefits	$81,000	$14,000	equivalent of 12-13 gallons of propane per day	$64,000/yr and $7,500/yr in heating offsets
Annual Operating Costs	$15,000	n.a.	$700	$12,000
Payback Period	5.5 years	4.9 years	n.a.	4 years

Source: U.S. EPA, *Methane Recovery from Animal Manures - The 1997 Opportunities Casebook.*

4.4.2 Large Scale Digesters

These digesters have large capacities and are often technologically advanced. Large scale digesters are generally heated and can therefore operate in relatively cold regions. Usually, large scale digesters require a significant capital investment, are complex to build and operate, and require large amounts of concentrated manure. These are particularly suitable at operations which handle manure as liquids (less than 10% solids) or slurry (10 to 20% solids). The type of large

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[42] Ibid.

scale digester used (i.e., plug flow or complex mix) depends on the manure quantity and characteristics.[43]

4.4.2.1 Plug Flow Digesters

Plug flow digesters are constant volume, flow-through units that decompose high solids (>11%) dairy manure (plug flow digesters only work with dairy scraped manure and cannot be used with other manures) to produce biogas and a biologically stabilized effluent. The plug flow digester design is a long tank, often built below ground level, with a gas-tight, expandable cover. The tank volume equals the volume of the manure input times the manure retention time, which is typically 15 to 20 days. Plug flow digester systems also include the manure collection system, mixing pit equipment, and an effluent storage system. [44]

To effectively operate a plug flow digester, manure should be collected and inserted daily into the mixing pit. Manure should be relatively free of contaminants such as sand, large volumes of sawdust, hay, or clumps of hair. The mixing pit allows the total solids concentration of the manure to be adjusted, if required. New manure is added daily which slowly pushes the older manure down the tank. The mixing pit is connected to the digester by a pipe entering below the surface of the manure.[45]

A gas-tight cover collects the biogas and maintains anaerobic conditions inside the tank. A greenhouse may be constructed or insulation used to protect the flexible covers and to maintain temperatures. Plug flow digesters may also be built with fired concrete tops requiring continuous gas use or separate gas storage bags. Biogas is collected with a pipe supported above the manure. The amount of methane produced is about 40 ft^3/cow/day. When digested manure reaches the end of the tank, it is removed and stored in a storage pond, tank, or other suitable manure storage structure.[46]

Ancillary benefits (apart from reduction in methane emissions and utilization of biogas) of utilizing plug flow digesters are:

- large reductions in offensive odours because volatile organic acids are digested by methane production bacteria;
- up to 90% reduction in Biological Oxygen Demand;
- greater than 99% destruction of pathogens, viruses, protozoa, and other disease-transmitting organisms;

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[43] US EPA, Options for Reducing Methane Emission Internationally - Volume II: International Opportunities for Reducing Methane Emissions - Report to Congress, October 1993, pg. 6-5.

[44] U.S. EPA, AgSTAR Technical Series: Plug Flow Digesters, February 1997, pg. 1-2.

[45] Ibid.

[46] Ibid.

- reduced costs for hauling manure to crops because methane producing bacteria reduce manure solids by up to 95%, making the nutrient rich material available to crops through pumps and commercial spray irrigation equipment; and
- improved nutrient application control because up to 70% of the organic nitrogen is converted into ammonia, the primary constituent of commercial fertilizer.

Economics for Actual Plug Flow Digesters in the U.S. (C$)

Farm Description	**15,000 total head with 5,000 milkers**	**350 milkers**	**400 milkers**
Capital Cost	$435,000	$270,000	$290,000
Electricity benefits	$180,000-$230,000/yr	$60,000/yr	$52,000/yr
Other benefits	n.a.	n.a.	• heat savings of $7,000/yr • sold manure solids worth $8,500/yr • reduced manure lagoon cleanouts estimated to be $13,000/yr.
Annual Operating Costs	$17,500-$22,000/yr	n.a.	n.a.
Payback Period	<3 years	n.a.	5 years

Source: U.S. EPA, *Methane Recovery from Animal Manures - The 1997 Opportunities Casebook.*

4.4.2.2 Complete Mix Digesters

Complete mix digesters are heated, constant volume, mechanically-mixed, tanks that decompose swine or dairy manure (3-8% total solids) to produce biogas and a biologically stabilized effluent. The basic complete mix digester design is a vertical, poured concrete or steel circular container, with a gas-tight collection cover. Because complete mix digesters are heated to optimize methane production, they can be economically sized for use in any climate.

To effectively operate the system, manure is collected daily in a mixing pit where the portion of total solids can be adjusted and the manure can also be preheated. Manure enters the digester vessel through either a gravity-flow or pump system. Manure is intermittently mixed within the digester vessel to prevent the formation of a surface crust. A gas-tight cover maintains anaerobic conditions and traps the methane that is produced. The gas is then collected through a pipe supported above the manure.

The amount of methane produced is about 5-8 ft^3/lb volatile solids (volatile solids are the organic portion of the manure and represent about 8 to 11% of the total manure). The digester volume equals the volume of the influent (manure and waste water) times the average manure retention time, typically between 15 and 20 days.

The methane produced in the digester is then removed, processed, and transported to the end use site. The remaining effluent manure flows from the digester and is stored in a storage tank or lagoon until it can be land applied. For dairy manure, solids may be separated out of the digested effluent and sold as soil amendments.

The same ancillary benefits that are derived when utilizing a covered lagoon or a plug flow digester are also realized when a complete mix digester is in operation, namely:

- reduction in odours;
- digestion converts organic nitrogen into ammonium compounds, significantly reducing the potential for ground and surface water contamination;
- digestion reduces BOD levels, reducing the potential for surface water contamination; and
- heated digestion significantly reduces harmful pathogens.

Economics for Complete Mix Digesters in the U.S. (C$)

Farm Description	**270 milkers**	**1,500 sow farrow to finish**	**700 head dairy**	**1,200 head farrow-to-finish swine farm**
Capital Cost	$725,000	$360,000	$290,000	$470,000
Electricity Benefits	$15,000/yr	$72,000/yr	$55,000-$61,000/yr	$87,000-$94,000/yr
Other Benefits	• sells 17,000-18,000 gallons of fuel oil equivalent/yr • effluent fertilizer value is $36,000/yr	• thermal benefits are $22,000/yr	n.a.	• $58,000 offsets in heating season
Annual Operating Costs	$6,000/yr	$7,000	$36,000	$12,000
Payback Period	n.a.	4-5 years	4 years	n.a.

Source: U.S. EPA, *Methane Recovery from Animal Manures - The 1997 Opportunities Casebook.*

4.4.3 Small Scale Digesters

Small scale digesters are typically up to $100m^3$ in total capacity, or a daily capacity of 3.5 m^3 capable of handling about 1,800 kg of manure daily. It should be noted that small scale digesters can be built in a variety of sizes with the capacity being tailored to fit the specific application. Typical sizes range from a 4 to 5 m^3 design, suitable for a single family running a small farm, up to 75 to 100 m^3 and larger. Small scale digester systems will produce about 0.5 to 1 m^3 of biogas per m^3 of digester volume. For example, the biogas produced in a 4.5 m^3 digester would provide sufficient biogas for domestic cooling, lighting, or refrigeration, in addition to fertilizer and animal feed supplements from the slurry effluent.[47] Small scale digesters are not usually heated. The IPCC assumed an efficiency of 70% for reductions in CH_4 emissions.

Small Scale Digester Construction Costs (C$/cubic meter volume)

Digester Type	Digester Volume (m^3)			
	4.5	7	20	50
Fixed Dome - Ferrocement	220	160	90	50
Fixed Dome - Poured Concrete	260	190	120	100
Floating Cover	350	300	190	150

Source: U.S. EPA, *Options for Reducing Methane Emissions Internationally - Volume I: Technological Options for Reducing Methane Emissions*, July 1993, pg. 7-17.

Operation and maintenance costs include labour, water and occasional parts, repairs and unexpected variable costs. The 8 m^3 and 20 m^3 fixed dome digesters (both ferrocement and poured concrete) require about 36 days of labour/year and about 1 litre of water is required per kg of manure handled. Annual costs of parts, repairs, and insurance for ferrocement and poured concrete is about $2.40 to $3.20/kg of manure handled for 8 m^3 digesters, and $1.45 to $2.40 per kg of manure handled for 20 m^3 digesters.

Costs recovered from small scale digesters include cost of the fuel replaced by biogas, and labour costs of gathering wood or crop stalks for burning. Assuming the fuel replaces LPG (priced at $0.75/litre) and that basic digesters produce 0.5-1 m^3 of biogas/m^3 of digester volume, the costs of alternative fuels avoided by the 8 m^3 fixed dome digesters are about $0.05-0.08/kg of manure handled and $0.06-0.012/kg of manure handled for 20 m^3 digesters.

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[47] U.S. EPA, Options for Reducing Methane Emissions Internationally - Volume I: Technological Options for Reducing Methane Emissions, July 1993, pg. 7-12.

Small scale anaerobic digesters are designed for regions where resource constraints limit the application of more advanced technologies (i.e., those digesters discussed in the previous sections). Small scale digesters are therefore most appropriate for rural, agricultural regions in tropical developing countries. The important factors controlling digestion efficiency are:

- manure handling and composition - the water content of the manure entering the digester must be controlled to maintain 7 to 9% total solids; and
- temperature - temperature in the digester should not drop below 30°C.

Small scale digester systems can be floating gas holders which have a steel, fiberglass or ferrocement roof that floats to accommodate the gas; flexible bag holders comprising a large rubber bag that expands and contracts according to the volume of gas; or the fixed dome system, a masonry construction with no moving parts.

4.4.3.1 Floating Gas Holders

Floating gas holders collect biogas by building a steel, fibreglass or ferrocement floating holder to form the roof of the digestive chamber. This floating cover is able to move vertically along internal or external guides. When gas is produced the holder rises to accommodate the increased volume; when gas is drawn off, the holder falls, maintaining a constant gas pressure. An air tight water or manure seal is formed around the bottom of the holder.

Floating gas holder systems have been installed in several countries, especially India. Experience indicates that corrosion often reduces the lifetime of steel floating covers. Another drawback to these systems is that the construction of the steel holder and guides is a relatively complicated and an expensive process and will at best only be feasible in regions with manufacturing capability.

4.4.3.2 Flexible Floating Bag Holders

Floating bag holders are perhaps the simplest digester to construct and operate. A large rubber bag contains the decomposing manure and collects the biogas. As biogas is produced and consumed, the flexible bag expands and contracts according to the volume of gas it contains.[48]

Floating bag holders have potential for application in certain conditions by virtue of their low cost, ease of production, transport, and the fact that there is virtually no on-site construction requirements.

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[48] Ibid, pg. 7-13.

4.4.3.3 Fixed Dome

Fixed dome systems combine the digester and gas storage components in a single, fixed unit. This allows the entire unit to be constructed from masonry (e.g., brick, cement hollow blocks, ferrocement) with no moving parts. This greatly reduces the complexity and cost of the system. As gas is produced it exerts a pressure of up to one meter water column on the digester contents; this pressure forces some slurry into the displacement pit, eventually balancing the gas pressure. The major problem associated with this system is the variable gas pressure.[49]

4.4.4 Slurry Digesters

Other types of anaerobic digestion systems are suitable for processing animal manures beyond the complete mix, plug flow for dairy, and the covered lagoon digesters. However, those digesters are the only ones now recognized by the U.S. Department of Agriculture's Natural Resource Conservation Service.

A number of other digester types have been shown to have technical and economic feasibility. As one example, a dairy farm in the U.S. has abandoned the plug flow approach and now employs a greatly simplified slurry-based "loop" digester, which further minimizes digester construction and operating costs. This slurry digester enables greater convective currents in the digester, thereby avoiding the solids crusting problem commonly associated with the plug flow design. [50]

It has been suggested that slurry digesters offer several additional benefits beyond their low cost to install and simplified operation. When combined with a mechanical scraping system for manure collection, little added water is required compared to hydraulic flushing. In addition, because the organic acids are not volatized, the methane and odour associated with manure decomposition can be minimized to the greatest extent possible.[51]

4.4.5 Mesophilic Digesters

Mesophilic anaerobic digesters are heated stirred tank reactors that operate at approximately 29-32°C. The system uses elective culturing (i.e., an appropriate feed regimen that selects for specific microbes).[52]

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[49] Ibid, pg. 7-14.

[50] U.S. EPA, Methane Recovery from Animal Manures - The 1997 Opportunities Casebook, pg. 2-6.

[51] Ibid.

[52] Symbiotics Environmental Research and Consulting, Inventory of Technologies to Reduce Greenhouse Gas Emissions from Agriculture, December 1996, pg. 15.

4.4.6 Other Types of Digesters

An anaerobic filter digester is being used at a dairy farm in Florida to treat liquid manure. The anaerobic filter was commercialized for industrial wastewaters in the late 1980's and relies upon a media substrate to retain the biomass within the reactor vessel. Filter material is usually made from ceramics, glass, plastic, or wood. The retention time for this "higher" rate digestion technology is typically one to two days. [53]

An Advanced Integrated Ponding System (AIPS) is being used in California. AIPS uses a submerged canopy covering a facultative pond where the organic wastes are completely converted into methane, nitrogen, carbon dioxide, and stable residues. The submerged canopy is potentially more cost-effective than conventional covered lagoons because it is not exposed to weather and other elements. The digester effluent from the AIPS is discharged into secondary pools and used as a growth culture for algae. [54]

Other types of anaerobic digesters discussed for farm applications, but not yet commercially used in the U.S. include upflow sludge blankets and sequencing batch reactors. Although these technologies offer the potential for reducing the number of days required for the anaerobic process, they are perceived to suffer from comparatively higher capital and operating costs, as well as a greater level of process and operational complexity than the types now in operation.

Currently R&D is on-going that combines the use of a reverse osmosis (RO) plant to treat discharged digester effluent. The pores of the RO membrane are so small that heterogeneous material is retained and only water molecules are allowed to pass. The result is a clean water fraction and a commercial standard fertilizer concentrated to about 10% of the original effluent volume.[55]

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[53] U.S. EPA, Methane Recovery from Animal Manures - The 1997 Opportunities Casebook, pg. 2-6 - 2-7.

[54] Ibid.

[55] Ibid.

Technical Assessment for Common Types of Digesters

Considerations	Covered Lagoons	Large Scale Digesters	Small Scale Digesters
Recovery Techniques	Impermeable Lagoon Covers	Complete Mix Plug Flow	Fixed Dome Floating Holder Flexible Bag
Gas Quality	Medium Quality (600-800 Btu/cf) (22-29 MJ/m^3)	Medium Quality (600-800 Btu/cf) (22-29 MJ/m^3)	Medium Quality (600-800 Btu/cf) (22-29 MJ/m^3)
Use Options	Electricity Generation Boilers, Refrigeration, Other Fertilizer, Feed Supplement, Other	Electricity Generation Boilers, Refrigeration, Other Fertilizer, Feed Supplement, Other	Electricity Generation Domestic Gas Use Fertilizer, Feed Supplement, Other
Farm Type	Dairy, Hog	Complete Mix (Dairy, Hog) Plug Flow (Dairy Only)	
Supplemental Heat Required	No	Yes	Yes
Availability	Currently Available	Currently Available	Currently Available
Capital Requirements	Low/Moderate	Moderate	Low
Technical Complexity	Low Technology	Moderate Technology	Low Technology
Applicability	Temperate, Tropical Flush Systems; Low % TS[2]	Temperate, Tropical 2-15% TS[2]	Temperate, Tropical 2-15% TS[2]
Methane Reductions	Up to 80%	Up to 70% or more	Up to 70%

Source: US EPA, *Options for Reducing Methane Emission Internationally - Volume II: International Opportunities for Reducing Methane Emissions - Report to Congress,* October 1993, pg. 6-4 and U.S. EPA, *AgSTAR Handbook, A Manual for Developing Biogas Systems at Commercial Farms in the United States*, July 1997, pg. 1-2.

[1] These are reductions which may be achieved at an appropriate individual site.

[2] Percent Total Solids (%TS) is a measure of the concentration of the manure in water.

4.4.7 Aerobic Composting

There are several types of aerobic composting technologies that are currently being developed in Canada. These systems use various different processes to aerobically compost liquid livestock manure to produce fertilizer which can be applied to fields or can even be sold on the commercial or consumer markets. The two large categories of aerobic composters are continuous and batch. Continuous system require that manure be fed into the composting system daily while batch composters may only need liquid manure to be fed into the system approximately 6 times over a 30 day period.

Aerobic composting has the potential to mitigate GHG releases from two sources. First of all, aerobic composting, through the utilization of manure to produce an organic fertilizer, reduces methane emissions. Secondly, the organic fertilizer has the potential to replace commercially produced fertilizers which cause significant nitrous oxide emissions. Organic fertilizers are much more stable than chemical fertilizers and are much less prone to leaching of nitrates either downward into the soil or upward into the atmosphere. One of the prominent technology developers in Canada for aerobic composting suggested that organic fertilizers produced through aerobic composting have the effectiveness to substantially reduce the current dependence on chemical fertilizers in Canada. Outlined below are descriptions of a few of the aerobic composting units that are near full-scale commercialization in Canada.

4.4.7.1 Batch Aerobic Composter

The batch aerobic composter is a concrete channel 7-12 feet wide, 6 feet deep and 50 feet long (length varies with size of operation) which is filled with straw and other suitable organic material such as sawdust or wood chips. Liquid swine manure is sprinkled over the straw until it is saturated. The channel floor contains suitable means for introducing and dispersing air into the mixture which will undergo a natural composting action. At specified time intervals, more liquid manure will be added and the mixture will be turned over by means of a turning device. The batch process takes 4 weeks. Once the compost has been stored and cured for an additional 28 days, it will be ready to be processed into usable organic fertilizer. This fertilizer can then be used on the farm or sold to nurseries, golf courses and on the retail market.

4.4.7.2 Enhanced Moisture Aerobic Compost System

An enhanced moisture aerobic compost system does not require any external heat energy but instead uses the potential energy available in the manure to evaporate water. Aerobic bacteria oxidize the organic matter, coverting the energy in organic material to heat energy. This system is not as costly to operate as an anaerobic processing system with an additional benefit of a marketable product.

The system works by mixing liquid hog manure with a dry bulking agent such as sawdust, peat or straw and composted using passively aerated composting or turned windrows with or without aeration. The principle upon which the system works is that the warm air rising from the composting material holds much more water than cool air entering the composting material.[56]

4.4.7.3 Continuous Vertical Aerobic Composting

Another separate technology is continuous vertical aerobic composting. This process involves three steps, namely:

- liquid/solid fractions separation and mechanical dewatering;
- thermophilic conversion of the solid fraction to humus in composting bioreactors; and
- treatment of the liquid fraction to the quality permitting its discharge into common recipients.

Separation of organic matter and nutrients and their transfer into solid form is carried out in two stages. Course solids are separated mechanically. Fine suspension, colloid forms and some dissolved substances are transferred to solid state by precipitation with calcium hydroxide in the high pH environment followed by separation of the precipitated suspension in a chemical reactor and by mechanic dewatering of separated chemical sludge.

High bioenergy content of the sludge can be used from composting of other carbon containing substrates (such as straw) which on their own do not contain sufficient amounts of nutrients and energy for composting. Added directly into incoming liquid manure, they bound dissolved and colloid substances f the manure and increase the overall efficiency of separation. If the substrates are not available or to supplement them, a part of the produced humus is recycled to the incoming manure for the same purpose.

Liquid fraction is treated in a biological reactor using activated sludge process with very low activated sludge loading, "superactivation" process. The treatment includes nitrification, denitrification, and biological dephosphorication. Biological sludge from the process is recycled back to liquid/slid separation and ultimately composting bioreactors.

The system produces one end-product, humus fertilizer, and one byproduct, treated effluent. Humus end product is an irreplaceably complex natural fertilizer and valuable product. It can be stored indefinitely, transported and applied where and when needed, and bagged or palletized, it can even be sold on the commercial or consumer market.

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[56] Agriculture and Agri-Food Canada, *Liquid Manure Recycling through a Modified Composting System: 1. Project Development*, October 1996.

4.4.8 Constructed Wetlands

Because of their high rate of biological activity, wetlands can transform many pollutants common to wastewater into nutrients that support further biological activity or into chemical forms less harmful to the environment. Barnyard runoff and milkhouse wastewater are two of the most promising applications for constructed wetlands.[57]

4.4.9 Bioreactors

AAFC is currently conducting R&D on a process that uses bioreactors to recover CH_4 emissions from livestock manure. This technology has been suggested to be quite similar to anaerobic digesters. Unfortunately, no details are available on this technology as AAFC is working in conjunction with a private partner to develop the technology.

AAFC is quite positive as to the viability of this technology as it is purposefully making the technology simple to maximize its applicability at Canadian farms. AAFC has planned to operate a pilot scale of the technology some time next year.

4.5 R&D Capabilities and Requirements

Agriculture and Agri-Food Canada (AAFC) is the primary organization in Canada conducting R&D with respect to controlling CH_4 emissions from livestock manure. AAFC has 19 research centres across Canada which conduct R&D on a wide range of topics. Several of these centres are presently conducting R&D in the area of controlling CH_4 emissions from livestock manure.

AAFC Research Centres Conducting R&D into Livestock Manure

Research Centre	Location	Area of Research
Dairy and Swine Research and Development Centre	Lennoxville, PQ	bioreactors
Centre for Food and Animal Research	Ottawa, ON	
Brandon Research Centre	Brandon, MB	
Pacific Agri-Food Research Centre	Summerland, BC	composting of hog manure
Potato Research Centre	Charlottetown, PEI	
Eastern Cereals and Oilseeds Research Centre	Ottawa, ON	composting of cow manure

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[57] Symbiotics Environmental Research and Consulting, Inventory of Technologies to Reduce Greenhouse Gas Emissions from Agriculture, December 1996, pg. 15.

Individuals involved with the Centres, and others, are part of the manure information network - an informal group organized to discuss and collaborate on R&D activities with respect to manure management.

In addition to Agriculture and Agri-Food Canada, universities and other institutions are also conducting research into various aspects of manure management. Some of the individuals who have been reported to work in this field are shown below.

Universities/Institutions Conducting R&D into Manure Management

University/Institution	Contact
McGill University	Ms. Susan Barrington
Guelph University	Mr. Claude Viau
University of British Columbia	Mr. Hugh Saben
University of Manitoba	Mr. Jan Olezkiewicz
Nova Scotia Agricultural College	Mr. Phil Warman
Alberta Research Council	Mr. Richard Coleman

While no anaerobic digesters are currently operational in Canada, several individuals are of the opinion that they are viable for manure management in Canada. It has been suggested that previous digester failures have contributed to poor technical perception held by the livestock industry, and have resulted in very limited biogas development recently. However, examining past failures has led to improvements and refinements in existing technologies and newer, more practical systems currently exist. Although there are only a few digesters that are operational in the U.S., several of these are operating in the northeastern U.S., a climate not unlike Canada's.

Private Canadian Companies Developing Anaerobic Digesters for Manure Management

Company	Location	Type of Digester
NovaTec Consultants Inc.	Vancouver, BC	Covered Lagoon
ADI Systems Inc.	Fredericton, NB	Plug Flow
Aquasol Technologies Inc.	Edmonton, AB	Plug Flow

There are three Canadian private sector firms that are currently developing and marketing anaerobic digester systems. None of these companies have sold on their systems in Canada, however all have recently developed newer versions of anaerobic digesters and are of the opinion that there is a large potential market in Canada.

Status and Distribution of Commercial Farm Biogas Systems in the U.S.

	Slurry	Complete Mix Digesters	Plug Flow Digesters	Covered Lagoon	Total
Operating	6	4	8	7	25
Not Operating	0	15	29	3	47
Under construction or planning phase	1	2	4	1	8
Started But Not Built	0	1	8	1	10
Total	7	**22**	**49**	**12**	**90**

Source U.S. EPA, *Methane Recovery from Animal Manures - The 1997 Opportunities Casebook*, pg. 1-2.

There are few, if any commercial farms (outside of pilot projects) in Canada that have installed aerobic composting systems. There are reportedly a few operating in the U.S. (e.g. Texas). Apparently, more farms in Europe have installed these systems. One of the primary reasons why farms in Europe are more advanced in the utilization of these systems is that the waste handling costs are much higher in Europe therefore providing more of an incentive to address manure at the farm. As a result of these high costs, the costs of the aerobic composing systems designed and utilized in Europe are also relatively high which has precluded their adoption in North America. Therefore, there is a relatively untapped market in North America for these systems. In addition, the Canadian developers of these systems are of the belief that the cheaper systems that they are designing here in Canada should be quite attractive to European farms.

There are several Canadian companies that are quite close to full-scale commercialization of their respective aerobic composting systems for manure. It is estimated that there are approximately 10 or so Canadian firms that are at various stages in the development of aerobic composting systems.

Canadian Firms Developing Aerobic Composting Systems

Company	Location
Global Earth Products	Utopia, ON
Sittler Manufacturing	Elmira, ON
Transform Compost Systems Ltd.	Agazzi, BC
EKOKAN Inc.	Rock Forest, PQ
Ecofluid Systems Inc.	Vancouver, BC
Down to Earth Ecofarm Products	Abbortsford, BC

4.6 Recommendations

There are proven technologies that exist that can reduce CH_4 emissions from livestock manure at Canadian farms. However currently, CH_4 emissions from livestock manure in Canada are for the most part uncontrolled.

Anaerobic digesters have been around for many years, but failed when applied in Canada a decade or so ago. However, there have been advances in these technologies since then and many of the anaerobic digesters that are currently operating in the U.S., are operating in the northeast, which has a climate similar to Canada. The CH_4 problem from farms is concentrated at large farms which promote the uncontrolled anaerobic digestion of liquid manure. There are not many of these farms in Canada and therefore a technology transfer program or additional R&D to ensure that these technologies are cost effective in Canada may be warranted.

Currently in Canada there is much more research being conducted on aerobic composting systems than anaerobic digesters. There are approximately 10 Canadian companies that are at various stages in the commercialization of this technology. Some of these firms are at the demonstration stage and have already been receiving inquiries from farms in the U.S. Canadian developers appear to be quite progressive in the advancement of aerobic composting systems with many of these developers believing that they are more advanced than their U.S. counterparts. There appears to be substantial potential for this technology. Environment Canada may want to foster the small number of companies in Canada that are currently developing this technology. Many have suggested that some timely financing could go a long way towards the commercialization of their technology and the penetration of the U.S. market.

Lastly, Environment Canada may also want to identify those farms which are the most likely candidates to control CH_4 emissions through one of the above, or other technologies.

5. Fertilizer Application

5.1 Summary

A wide variety of farm management practices and technologies that have been developed or are in the development stage can reduce N_2O emissions from fertilizer application.[58] The IPCC has estimated that N_2O emissions from agriculture could be reduced by 9-26% by improving agricultural management with available techniques. Using an estimate of a 22% reduction for Canada results in a 3 kt reduction in N_2O emissions or approximately 900 kt of CO_2-equivalent. This is a low capital cost and operating cost option (+/-5 \$/tonne-CO_2 reduced has been assumed). Growers are likely to realize benefits through lower fertilizer application.

In addition to existing measures, other practices or technologies such as precision farming, nitrification inhibitors and slow release fertilizers are still being researched and refined to improve the likelihood of their widespread adoption by the farming community. Agriculture and Agri-Food Canada (AAFC) as well as several Canadian universities have studied these and various other approaches to reduce N_2O emissions from fertilizer application over the last 5 years.

Many of the existing technologies and practices have been adopted by a small portion of the farming community and have resulted in a net economic benefit to the farmers. Canadian farmers could therefore potentially reduce a significant portion of their N_2O emissions from fertilizer application at no or little economic cost.

To maximize the application of current and future farming practices and technologies, more research is required to ensure that the various approaches are refined to the point that farmers will consider their adoption. AAFC has indicated that they do not expect the necessary level of funding to be made available for them to conduct the required research and development in the future. Environment Canada has therefore a significant role to play to ensure that the current technologies and practices are refined and adopted and that some of the evolving technologies are improved so that they too are adopted by the Canadian farming population.

5.2 Background

Nitrogen is an essential nutrient required in soil to enable crops to grow. Soil contains a natural level of nitrogen. Nitrogen based fertilizers are used to increase the nitrogen content of soils to a point which maximizes crop yield. Different types of nitrogen based fertilizers are applied in

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[58] Carbon dioxide emissions from soil are not included in this investigation.

Canada. Urea and anhydrous ammonia are the two most commonly used fertilizers, together representing approximately 72% of the mineral nitrogen applied as fertilizer annually in Canada.

Nitrogen Fertilizer Consumption in Canada (1993), by Crop

Crop	Area (000 Ha)	% of Crop Fertilized	Rate of Application (Kg/Ha)	Consumption (kt)	Percentage of Nitrogen Consumption
Barley	4,240	85	60	216	18
Maize	993	90	150	134	11
Oat	1,357	60	45	37	3
Rye	159	60	40	4	<1
Wheat	12,626	80	45	455	38
Potato	126	95	100	12	1
Rapeseed	4,063	95	65	251	21
Soybean	720	95	10	7	<1
Flax	501	75	60	23	2
Others	8,056	35	25	71	6
Total	**32,841**			**1,210**	**100%**

Source: Food and Agriculture Organization, *Fertilizer Use by Crop.*

The primary crops which nitrogen based fertilizers are applied to are: wheat (38%), rapeseed (21%), barley (18%) and maize (11%). Combined, these four crops represent approximately 90% of nitrogen based fertilizer use in Canada.

5.3 Emissions and Trends

When nitrogen-based fertilizers are applied to soil, N_2O emissions generally increase unless the amount of nutrient applied precisely matches plant uptake and soil capture. N_2O emissions from fertilizer application occurs due to anaerobic and aerobic processes. When either inorganic or organic fertilizers are applied to soil, most of the nitrogen is oxidized to nitrates before it is taken up by the plants (this process is referred to as nitrification).

Anaerobic emissions of N_2O occur when soils become waterlogged. The nitrates can then be reduced by facultative anaerobic bacteria to N_2O, which can then be further reduced to N_2 before it is lost to the atmosphere (this process is referred to as denitrification).[59]

Several factors control rates of the two microbial processes (nitrification and denitrification) that result in N_2O emissions. Among these variables are soil water content, temperature, nitrate or ammonium concentrations, available organic carbon for identification, and pH.[60]

Canadian Fertilizer Use and Related N_2O Emissions in 1995

Fertilizer Material	**Quantity (tonnes)**	**N Content (tonnes)**	**Average Loss (% N)**	**N_2O (tonnes)**
Nitrogen				
Urea	1,304,730	600,176	0.11	1,037
Ammonia Sulphate	205,330	43,119	0.12	81
Ammonium Nitrate	256,697	87,957	0.26	369
Anhydrous Ammonia	553,727	442,581	1.63	11,336
Nitrogen Solutions	232,906	66,029	0.11	114
Other Nitrogen	3,199	0	0.11	0
Calcium Ammonium Nitrate	32,849	8,470	0.03	4
Phosphate				
Monoammonium Phosphate	937,031	103,073	0.12	194
Diammonium Phosphate	180,785	32,541	0.12	61
10-34-0	1,705	238	0.11	0
Other Fertilizers	293,804	64,171	0.11	111
Total	**4,002,765**	**1,448,355**		**13,300**

Environment Canada, *Trends in Greenhouse Gas Emission, 1990-96.*

Current Canadian estimates of N_2O emissions from the application of anhydrous ammonia are considered to be high because the application rates in Canada are generally low.

The OECD suggests that 1% of applied nitrogenous fertilizers are directly released as nitrous oxide although they recognize that there is a great deal of uncertainty over the estimation of these

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[59] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, April 1997.

[60] Intergovernmental Panel on Climate Change, Climate Change 1995. Impacts, Adaptations and Mitigations of Climate Change, 1996, pg. 761.

emissions. The OECD also estimates that an additional 0.75% of N applications will evolve to the atmosphere as N_2O resulting from N leaching, runoff and NO_x and NH_3 volatization.

However, based on current estimates, the application of anhydrous ammonia is the source of 85% of fertilizer related N_2O emissions in Canada. Compared to anhydrous ammonia, 750,000 more tonnes of urea are applied in Canada (which corresponds to a total of 158,000 more tonnes of nitrogen nutrient applied with urea than anhydrous ammonia). However, urea only represents approximately 8% of N_2O emission while anhydrous ammonia represents 85%. This disparity is due to the fact that anhydrous ammonia has such a high emission factor (i.e., 1.63%) compared to urea (i.e., 0.11%) and all the other nitrogen based fertilizers.

A significant increase in N_2O emissions from fertilizer application in Canada has occurred in the first half of the 1990's (i.e., >24%). However over the last three years, N_2O emissions have remained stable. The U.S. generally have N_2O emissions from fertilizer application of roughly 13-14 times that estimated in Canada. Their emissions have increased by 5% from 1990-1995.

Emission Trends from Fertilizer Application in North America

Year	N_2O Emissions (kt)	
	Canada	U.S.
1990	11	159
1991	11	162
1992	12	163
1993	13	171
1994	13	174
1995	13	167

It should be noted that these emission estimates are questionable as international work suggests that up to 50% of N_2O releases from fertilizer may not be included in current estimates. The emission estimates are based on emission factors developed from on-field emission measurements, while much of the fertilizer applied to fields is released off-site due to runoff and losses of NH_3. Future emission estimates for Canada may reflect these additional sources as the new GHG inventory procedures document, published by the IPCC, details some new methodologies to estimate emissions from these additional sources.

The rationale for this increase in N_2O emissions has been the increase in fertilizer application, specifically nitrogen based fertilizers, over the last decade. Of the three nutrient based fertilizers that are applied in Canada, only nitrogen based fertilizers have seen an increase in consumption (in terms of the amount of nutrient applied) over the last decade. Both phosphate and potash based fertilizers have actually had their consumption (in terms of nutrient applied) decline from 1986-1996. Therefore, the increase in fertilizer consumption in Canada can be entirely attributed to the application of nitrogen based fertilizers.

Trends in the Consumption of Fertilizer in Canada

Year Ending June 30	**Total Fertilizer Sold**	**Nutrient Content (tonnes)**		
		Nitrogen	**Phosphate**	**Potash**
1996	4,829,045	1,576,201	658,416	333,253
1995	4,556,470	1,448,356	628,450	309,899
1994	4,536,882	1,405,925	641,187	328,023
1993	4,217,974	1,305,806	615,862	327,600
1992	4,070,613	1,253,288	592,227	310,225
1991	3,921,614	1,157,763	578,199	337,891
1990	4,101,942	1,196,292	613,577	359,843
1989	4,048,225	1,160,166	614,369	356,142
1988	4,241,298	1,187,653	634,475	404,040
1987	4,068,656	1,144,541	626,259	369,890
1986	4,229,991	1,220,721	695,110	370,201

Source: Agriculture and Agri-Food Canada, *Canadian Fertilizer Consumption, Shipments and Trade.*

5.4 Technologies to Reduce Emissions

It has been suggested that N_2O emissions from fertilizer application can be reduced through nitrogen-management practices that: (i) optimize the crop's natural ability to compete with processes whereby plant available nitrogen is lost from the soil-plant system (i.e., denitrification and leaching); and (ii) lower the rate and duration of these loss processes.[61]

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[61] Centre for Agricultural Science and Technology, Preparing U.S. Agriculture for Global Climate Change, June 1992, pg. 76.

Practices to Improve Efficiency of Use of Synthetic Fertilizer and Manure N in Agriculture and Expected Reduction of N_2O Emissions Assuming Global Application of Mitigation Practices

Practice Followed	Estimated Decrease in N_2O Emissions
	(Mt N/yr)
Match N Supply with Crop Demand Use soil/plant testing to determine fertilizer N needs Minimize fallow periods to limit mineral N accumulation Optimize split application schemes Match N application to reduced production goals in regions of crop overproduction	0.24[a]
Tighten N Flow Cycles Integrate animal & crop production systems - manure reuse in plant production Maintain plant residue N on the production site	0.14[b]
Use Advanced Fertilization Techniques Controlled-release fertilizers Place fertilizers below the soil surface Foliar application of fertilizers Use nitrification inhibitors Match fertilizer type to seasonal precipitation	0.15[c]
Optimize Tillage, Irrigation, and Drainage	0.15[d]
Total	**0.68**

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change*, 1996, pg. 763.

[a] Assumed that fertilizer N use efficiency can be increased to save 20% of N applied in North America, Europe, and FSU.

[b] Tightening N cycles may decrease the need for 20% of the N that is used currently in North America, Europe, and FSU, thus saving 20% of fertilizer and reducing N_2O from manure by the same amount where applicable.

[c] Controlled-release fertilizers, nitrification inhibitors, and matching fertilizer type with seasonal precipitation can decrease N_2O emissions 40-90%. The above table assumes that 10% of all fertilizer derived N_2O production can be decreased by 50%.

[d] There is little published data to confirm this assumption. A conservative assumption of a 5% decrease that can be achieved globally, is used.

By better linking nitrogen supply to crop demand and more closely integrating animal waste and crop-residue management with crop production, N_2O emissions could be reduced globally by approximately 0.38 Mt N_2O-N. Additional improvements in farm technology (e.g., use of controlled-release fertilizers, nitrification inhibitors, timing, and water management) should result in improved nitrogen use efficiency and further reduce N_2O emissions by an estimated 0.30 Mt N_2O-N.

Worldwide, it has been estimated that N_2O emissions from agriculture could be reduced by 9-26% by improving agricultural management with available techniques.[62] Due to these emission reduction possibilities, Codes of Good Agricultural Practice have been developed in several OECD countries which have specified these "best management practices" and "clean technologies". In addition, Actions 17 & 18 of the U.S. Climate Action Plan, which are aimed at reducing the use of fertilizers and pesticides and improving the efficiency of fertilizer nitrogen use, are forecast to achieve 2.7 MMTCE and 4.5 MMTCE reductions in methane emissions by the year 2000 respectively.[63]

Other agronomic practices that can be used to reduce N_2O emissions include: reduce ammonia emissions; avoid soil compaction; minimize use of anhydrous ammonia; avoid concentrating urea in the soil; establish a forage crop after herbicide application; lime acid soils; apply liquid manure as close as possible to soil surface; reduce straw bedding in solid manure; and install drainage systems.[64]

Five technologies or management practices to reduce N_2O emissions from fertilizer application are discussed in this section, namely:

- fertilizer management practices;
- nitrification inhibitors;
- irrigation water management;
- organic farming; and
- substitution among fertilizers.

In some work to date, it has been assumed that 2/3rds of the N_2O from N applied as manure or synthetic fertilizer is emitted directly from agricultural systems. The remaining 1/3rd is emitted indirectly as a result of runoff, nitrate leaching, and transfer of N to other sections of the ecosystem through NH_3 and NO_x emissions. It should be noted that only the direct N_2O emissions are easily controllable by on-farm management. However, management options that reduce the amount of external nitrogen required to produce a crop will reduce indirect N_2O releases.[65]

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[62] Organization for Economic Cooperation and Development, Policies and Measures for Common Action Working Paper 7 - Agriculture and Forestry, Identification of Options for net GHG Reduction, July 1996, pg. 31.

[63] Ibid, pg. 26.

[64] Environment Canada, Agriculture Forum on Climate Change: Opportunities for Canadian Agriculture - Summary of Proceedings, January 25-26, 1997, pg. 14.

[65] Intergovernmental Panel on Climate Change, Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change, 1996, pg. 763

5.4.1 Fertilizer Management Practices

A better matching of mineral fertilizer to crop requirements would result in a reduced demand for fertilizer and consequently reduced N_2O emissions. This increased efficiency can be achieved by:[66] [67]

- using nitrogen testing kits to more closely match crop requirements to nutrient inputs;
- regularly calibrating machinery to ensure accurate delivery of fertilizers;
- using slow release products and the incorporation of compounds that inhibit the conversion of one nitrogen compound to another (e.g., nitrification inhibitors);
- paying careful attention to the frequency, timing and appropriate placement of fertilizer applications;
- dispensing with the maintenance concept, which fails to recognize the amount of residual N in the soil and the soil's nitrification potential;
- adjusting the rate of N to a reasonable yield goal for the specific crop and field or soil;
- placing N deep enough in the soil to lower the N_2O/N_2 ratio when denitrification does occur; and
- taking into account soil N mineralization and the N from legumes, manures, organic wastes, irrigation water and other potential sources.

These practices will improve synthetic fertilizer and manure nitrogen use efficiency. The rationale in limiting N_2O emissions is that if fertilizer N is utilized more efficiently by the crop, the amount of N needed to meet the growing demand for food will be less and therefore less N_2O will be emitted. Timing and amount of fertilizer N application should have a goal of leaving as little residual N in the soil during the noncropped periods of the year as possible.[68]

It has been estimated that increased fertilizer efficiency has the potential to reduce N_2O emissions by 0.3-0.9 Mt N_2O-N/yr globally. In addition, fertilizer production is very energy intensive so by reducing fertilizer use, and therefore production, CO_2 emissions will also be reduced. Ancillary benefits of reduced fertilizer use include decreased contamination of surface and ground water; reduced fertilizer costs; and improved crop yields.[69]

Applying fertilizer at the optimum time will decrease the level of N_2O emissions (i.e., if fertilizer is applied in the fall or early spring it increases N_2O emissions whereas if the fertilizer is mixed

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[66] Organization for Economic Cooperation and Development, Policies and Measures for Common Action Working Paper 7 - Agriculture and Forestry, Identification of Options for net GHG Reduction, July 1996, pg. 26.

[67] Centre for Agricultural Science and Technology, Preparing U.S. Agriculture for Global Climate Change, June 1992, pg. 76.

[68] Ibid.

[69] Symbiotic Environmental Research and Consulting, Inventory of Technologies to Reduce Greenhouse Gas Emissions from Agriculture, pg. 16-17.

with the seeds or applied just after the seeds, there is not as much N_2O emission). Negative yield impacts are not thought to occur if fertilizer is applied with or just after the seeds, and in fact it is thought that beneficial yield results may occur.

5.4.2 Nitrification Inhibitors

Nitrification inhibitors are chemicals applied with fertilizers to maintain the added nitrogen as ammonium. Nitrification inhibitors stabilize fertilizer applied as NH_3 or in the NH_4+ form by inhibiting activity of the *Nitrosomonas* bacteria in the first step of the nitrification process.

Nitrogen losses are reduced if applied nitrogen remains in the NH_4+ form for several weeks after application, especially when applied in the fall or when there may be heavy rainfall during the spring. An inhibitor, such as nitrapyrin or acetylene, can be effective in many field crop situations.[70]

5.4.3 Irrigation Water Management

Usually emissions of denitrification gases occur immediately following each irrigation. Since N_2O can be further altered to N_2 during transport to the soil surface, there is greater opportunity to decrease the N_2O/N_2 ratio of the resulting gases when the mineral N is placed deeper in the soil.

Infrequent irrigation (compared to more frequent irrigation) decreases the number of denitrification cycles and also helps move soluble N deeper into the soil where supplies of O_2 are more limited which reduces the amount of N_2O that may form from N_2. Ancillary benefits are improved water quality and water conservation.[71]

It should be noted that with the same amount of irrigation water applied, very frequent irrigations tend to result in the largest amount of denitrification, whereas infrequent irrigation may increase leaching losses. Therefore, a balance would need to be drawn between these two types of N-losses.[72]

If nitrogen is applied to a dry field, there are not a significant level of N_2O emissions. However, if nitrogen based fertilizers are applied to water saturated fields, then there will be significantly more N_2O emissions. Ontario and Quebec have much more water saturated soils than the prairies

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[70] Centre for Agricultural Science and Technology, Preparing U.S. Agriculture for Global Climate Change, June 1992, pg. 77.

[71] Symbiotic Environmental Research and Consulting, Inventory of Technologies to Reduce Greenhouse Gas Emissions from Agriculture, pg. 16-17.

[72] Centre for Agricultural Science and Technology, Preparing U.S. Agriculture for Global Climate Change, June 1992, pg. 77.

and apply more nitrogen than farmers on the prairies. These two factors combined result in more N_2O emissions being generated in Ontario and Quebec than on the prairies.

5.4.4 Organic Farming

Organic farmers do not use any nitrogen based fertilizer. The only fertilizer that they use is rock phosphate, which is not the typical phosphate fertilizer. Organic farmers grow more legumes in their rotation such as peas, lentils and green manure. Green manure is a type of legume that is disked into the ground and therefore fertilizes the soils with nitrogen. The most common green manure on the prairies is sweet clover.

Organic farmers can grow any type of wheat. The green manure is mixed with wheat and planted the first year. As the green manure has very little growth the first year, a good wheat crop is harvested. The second year is the main sweet clover growth period. The second year sees no wheat crop and the sweet clover is disked into the ground. The third year is another wheat crop based on the nitrogen fertilizer from the sweet clover.

Organic farming results in a slower release of nitrogen which is evenly spread throughout the growing season as compared to fertilizers which have a big pool of N_2O releases right after the fertilizer is applied.

However others in the industry note that even if organic farming is practiced, the plants that are disked into the soil will still provide the nitrates to the crops which will result in the nitrification process and the resulting N_2O emissions. The plant material provides the required nitrogen in mineral form. Using organic matter as a source of nitrogen may result in smaller nitrogen losses at the beginning of the season when compared to fertilizer, but it will have a relatively even level of losses throughout the season, whereas fertilizers may have a large loss at the beginning of the season and a smaller loss throughout the remainder of the season.

The use of green manure is not widespread among conventional farmers. It is estimated that in the dry region of the prairies, only 5% of conventional farmers use green manure. Organic farmers get a higher price premium per bushel for their wheat as compared to what the conventional farmer receives.

The Centre for Agricultural Science and Technology have suggested that the picture for legumes is unclear. Eichner (1990) estimated that 0.17 to 2.4% of total global emissions of N_2O comes from cultivated legumes. If the area of cropland devoted to legumes increases significantly or if leguminous fields emit more N_2O that fertilized fields, dual cropping with legumes or rotating hectares under cultivation with legumes as an alternative to N fertilizer use could increase the atmospheric burden of N_2O.[73]

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[73] Ibid, pg. 60.

5.4.5 Substitution Among Fertilizers

After urea, anhydrous ammonia is the second most popular nitrogen based fertilizer. For instance, focusing on just the nitrogen based fertilizers in the 95/96 crop year, urea fertilizers were responsible for 46% of the nitrogen nutrients deposited on Canadian farmland, anhydrous ammonia was responsible for 39% and other nitrogen based fertilizers were responsible for 15%. It should be noted that some phosphate and potash based fertilizers also deposit nitrogen nutrients on farmland and were left out of the above calculation.

Recall that 85% of N_2O emissions from Canadian fertilizer applications have been estimated to emanate from anhydrous ammonia fertilizers. As mentioned, this is attributed to its high emission factor (i.e., 1.63% average loss of nitrogen). However, other literature provides emission factors different than those Environment Canada has applied. For instance, one study summarized data on relative emissions per unit of applied N which ranged from 0.001 to 0.5%, 0.011 to 1.8%, and 0.12 to 2.08% from nitrate, anhydrous and urea fertilizers respectively.[74] Researchers interviewed for this study suggested that urea fertilizers may contribute more N_2O emissions per unit of N applied than anhydrous ammonia fertilizers.

If the emission factors outlined in Environment Canada's GHG inventory are used, then Canadian farmers can reduce N_2O emissions by substituting anhydrous ammonia for other nitrogen based fertilizers. The alternative nitrogen based fertilizers that are available are urea, ammonia sulphate, ammonium nitrate, nitrogen solutions and calcium ammonium nitrate.

Discussions with suppliers of fertilizer in Canada as well as others in the industry indicate that individual nitrogen based fertilizers are completely substitutable with each other. The application of the various forms of nitrogen based fertilizers varies depending on the current price of the fertilizer as well as the time available to fertilize the soil (i.e., anhydrous ammonia takes longer to apply). Therefore, there is nothing to exclude the use of other forms on nitrogen based fertilizers (e.g., urea, ammonium nitrate, etc.) on the farmland that is currently being fertilized by anhydrous ammonia.

However, more research would be required to concretely determine the relative emission factors for urea and anhydrous ammonia before this could be considered a legitimate tool to reduce N_2O emissions.

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[74] Ibid.

5.5 R&D Capabilities and Requirements

A substantial amount of research has been conducted in Canada on how to reduce nitrous oxide emissions from fertilizer application. Much of the work has been focused on quantifying the degree that nitrous oxide emissions are emitted from fields under a wide variety of farming practices.

Agriculture and Agri-Food Canada (AAFC) and various universities in Canada share the R&D that is conducted in Canada in this area. Approximately 5-6 of AAFC's research centers are presently conducing research or have conducted research on this issue while roughly the same number of universities have addressed this issue.

Organizations Conducting R&D to Reduce N_2O Emissions from Fertilizer Application in Canada

Agriculture & Agri-Food Canada	Universities
Mr. Ray Desjardins (Eastern Cereal and Oilseed Research Centre)	Dr. Eric Beauchamp (University of Guelph)
Ms. Elizabeth Pattey (Eastern Cereal and Oilseed Research Centre)	Dr. Claudia Wagner-Riddle (University of Guelph)
Mr. Henry Janzen (Lethbridge Research Centre)	Dr. Gary Kachanoski (University of Guelph)
Mr. Reynald Lemke (Lethbridge Research Centre)	Dr. Dave Burton (University of Manitoba)
Mr. Chi Chang (Lethbridge Research Centre)	Dr. McKenney (University of Windsor)
Dr. John Paul. (Pacific Agri-Food Research Centre)	Dr. Dan Pennock (University of Saskatchewan)
Mr. Craig Drury (Greenhouse and Processing Crops Research Centre)	Dr. A.F. MacKenzie (McGill University)
F.P. Chalifour (Soils and Crops Research and Development Centre)	
Mr. Felipe Rochette (Soils and Crops Research and Development Centre)	
Dr. V.O. Biederbeck (Semiarid Prairie Agricultural Research Centre)	

The area that the most research is being conducted on currently is precision farming. Historically, farmers have applied a blanket cover of fertilizer to fields or in other words, the same quantity of fertilizer was applied at all points in a field. However, precision farming recognizes that different areas of a field require different amounts of fertilizer. For instance, one specific section of a field may require only ¼ of the amount of fertilizer that another section of the field requires. Applying only the amount of fertilizer that certain sections of a field require has favourable economic implications for reducing fertilizer use as well as achieving reductions in N_2O emissions.

5.6 GHG Reduction Costs

There has not been a significant level of economic analyses undertaken on the practices to reduce N_2O emissions from fertilizer application. The rationale for this lack of work is that some of the practices may not be used by a large number of farmers and where they are, they relate complex farming systems and it is therefore difficult to isolate costs and benefits.[75] However it is logical to assume that farmers will not volunteer to implement practices to reduce greenhouse gas emissions. Implementation of these measures will only occur if the grower is convinced that the profitability of the farm will improve if these practices are implemented.[76]

The IPCC have suggested that mitigation options to reduce N_2O emissions are likely to increase rather than decrease crop and animal productivity. Economic analyses of these emission reduction options should show positive economic as well as environmental benefits.[77] In addition, the Centre for Agricultural Science and Technology have suggested that the use of fertilizer to maximize economic yield is consistent with minimizing N_2O emissions.[78]

Fertilizer management practices, nitrification inhibitors and irrigation water management technologies are all available and have low reported capital costs.[79] These practices are more likely to be economically feasible on crops that have high N demands (e.g., corn, cotton and wheat). Because these practices already are being implemented to some extent, only minimal institutional programs may be needed to increase their level of use.[80]

As several of the farm management practices (as well as other technologies) are being implemented at farms in Canada and worldwide, there would appear to be a net economic benefit

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[75] Organization for Economic Cooperation and Development, Policies and Measures for Common Action Working Paper 7 - Agriculture and Forestry, Identification of Options for net GHG Reduction, July 1996, pg. 32.

[76] Intergovernmental Panel on Climate Change, Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change, 1996, pg. 765.

[77] Ibid, pg. 764

[78] Centre for Agricultural Science and Technology, Preparing U.S. Agriculture for Global Climate Change, June 1992, pg. 60.

[79] Symbiotic Environmental Research and Consulting, Inventory of Technologies to Reduce Greenhouse Gas Emissions from Agriculture, pg. 26.

[80] Intergovernmental Panel on Climate Change, Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change, 1996, pg. 765.

to utilizing these approaches. While some of the available practices will result in a net cost to be incurred by farmers, it is safe to assume that many of today's farmers in Canada can help to reduce N_2O emissions and at the same time enjoy a net economic benefit. The challenge is to persuade large numbers of farmers to adopt these new approaches and practices.

5.7 Recommendations

Agriculture and Agri-Food Canada have conducted a substantial amount of research with respect to N_2O emissions from fertilizers and soils in general over the last five years as part of their greenhouse gas research program. Substantial progress has been made during this period to better understand the processes which lead to N_2O emissions as well as to develop techniques to reduce the level of N_2O emissions. However, leading researchers in this area at AAFC point out that funding for future work will not be at the same level as in the past.

While progress has been made, substantial research still needs to be conducted to ensure that the farming practices and technologies are developed to the point that the maximum number of farmers in Canada adopt them. Meanwhile, there are still large uncertainties in the level of emissions from certain fertilizers (e.g., urea vs. anhydrous ammonia). Other promising practices, such as precision farming and slow release fertilizers are only at the infancy stage in terms of their research and development and require more research to make them more cost effective to utilize.

The IPCC have estimated that approximately 20% of N_2O emissions from fertilizer application can be reduced by widespread adoption of various farm management practices and technologies. In Canada that would result in approximately a 3 kt reduction in N_2O emissions or about 900 kt of CO_2 equivalent. A significant portion of these emissions could be reduced at a net economic benefit or at a cost that is below many of the control options identified within the other non-energy GHG emitting sectors.

Technology development and application in this area needs to built upon the work already undertaken by AAFC as well as Canadian universities (e.g., precision farming, nitrification inhibitors, slow release fertilizers) which have proven to be promising but are not at the stage of development to be widely adopted by the farming community.

6. Landfill Gas

6.1 Summary

Potential GHG emissions from landfill for 1995 is estimated at 27.2 Mt. However, actual emissions were 21.5 Mt because of existing controls, with 18.2 Mt of that total being methane (expressed as CO_2-equivalent in terms of global warming potential). Some of the methane potential released from landfills is already being captured and used as an energy source or merely being burned to form CO_2, a gas with much lower global warming potential.

There are many options to reduce GHG emissions from landfills. One option is to collect, treat and use the methane in the LFG as a fuel. This augments the reduction of GHG emissions since the methane potentially displaces energy sources which have GHG emissions associated with their production and use. The methane fuel can be used on-site or near the landfill for heating purposes, generation of electricity, in co-generation systems offering high energy-efficiency, or can be compressed for use as a transportation fuel. Another option is to combust the methane in a flare without using it as a fuel source at all.

The costs to reduce GHG emissions from landfills relate to the level of emissions reduction desired, as well as the technology options adopted. A low cost option to achieve 20 to 30% reduction is to capture, collect and flare (i.e., oxidize) the methane generated from the largest sites. This option has no associated direct financial incentive. Some of the landfills generate enough methane to support a larger investment in gas utilization equipment, such as electrical generating equipment. This option is more capital intensive but can provide a return to investors, through sale of the electricity. The greatest portion of the costs in achieving a higher (10 to 20% more) level of GHG reduction is associated with reducing emissions from thousands of small landfills spread across Canada. Even flaring at these sites could cost hundreds of millions of dollars.

The basic technology infrastructures for addressing emissions and utilizing methane available at large landfill sites already exists and has been applied successfully at sites in Canada, the United States and other countries. However, technology to lower the costs of addressing small sites where the rate of methane is low needs to be researched and developed.

6.2 Emissions and Trends

Methane, carbon dioxide, minor amounts of oxygen and nitrogen, trace amounts of hydrogen sulphide (H_2S), hexane, 1-1-1-trichloroethane, methylene chloride, and other volatile substances result from the decomposition of solid waste and are released from waste-containing landfills.

This mix of substances is referred to as landfill gas (LFG). Typically the ratio of methane to carbon dioxide is approximately 50:50, but can range substantially from one landfill to another, as well as over the life span of a landfill site.

An estimated 869 kilotonnes of methane was released from Canadian landfills during 1995[81]. This is equal to approximately 18.2 Mt of CO_2-equivalent in terms of global warming potential. The actual amount of carbon dioxide released from landfills is estimated to be equal to the amount of methane, on a volume basis[82], although greater on a weight basis due to the higher molecular weight of the carbon dioxide. However, on a global warming potential basis the amount of carbon dioxide, representing approximately 3.3 Mt, or 15% of the net total emitted from landfills[83], is substantially less than that contributed by methane.

Emissions From Landfills

	Potential Emissions	**Controlled**	**Net Emission**
		($Mt\text{-}CO_2$-Equivalent)	
Methane	23.9	5.7	18.2
Carbon dioxide	3.3	0.0	3.3
Total	27.2	5.7	21.5

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[81] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, April 1997.

[82] Ibid

[83] The report by Jaques, et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", does not estimate carbon dioxide emissions from landfills explicitly. The assumption is that the carbon dioxide stored in landfills and emitted as LFG is taken into account by models dealing with soil sequestration. An explicit approximation of the carbon dioxide emitted from LFG has been included here.

Estimated Emissions and Reduction Potential From Different Landfill Sizes

Size of Landfill (million tonnes of waste)	Estimated Number of Landfills in Canada	Range of Annual Methane Production	Portion of Total (869 kt/yr) Methane Generated	Estimated Portion of GHG Already Controlled	Remaining Amount of GHG for Potential Control	Potential to Control (@ 50% capture & 83% efficiency)
		(kt/yr/landfill)			(Mt-CO_2-eq)	(Mt-CO_2-eq)
Small (less than 2)	7,000 to 10,000	0 to 10	35%	4%	6.4	2.6
Medium (2 to 8)	30 to 100	5 to 75	50%	10%	9.0	3.7
Large (greater than 8)	10 to 20	10 to 120	15%	60%	2.8	1.2
Total / overall*	~10,000		100%	24%	18.2	7.50 (41% of methane) (35% of total CO_2)

Estimates are very rough and are meant to indicate the weight of emissions from different sized landfills.

A portion of the methane available in LFG is already being captured and oxidized to carbon dioxide. As of December 1995, there were approximately 25 to 30 landfill sites in Canada where LFG extraction systems have been installed, or were under construction. The amount of methane reduction has been estimated at 270 kilotonnes or 5,700 kilotonnes of CO_2-equivalents[84]. At nearly half of these sites, methane is collected and utilized as an energy source for heating purposes or for generation of electricity. At the other sites, the LFG is flared.

Most of the very large sites (landfills with greater than 8 million tonnes of waste capacity) already have gas collection and treatment facilities. There may be a few very large sites which have yet to install collection and treatment systems. A smaller percentage of medium sized landfills (between 2 and 8 million tonnes of waste capacity) have yet to install collection and treatment systems. It is estimated there may be between 30 and 100 sites across Canada in this category. A low portion (less than 5%) of the thousands of small sites (less than 2 million tonnes of waste capacity) across Canada have installed gas collection systems.

The business as usual scenario is that emissions from landfills will increase approximately 25% between the 1995 and 2010 (Environment Canada). This scenario assumes no waste diversion to composting or increase in recycling programs. Emissions are expected to increase in line with increases in human population.

6.3 Reduction Technologies

There are many options to reduce GHG emissions from landfills. One option is to collect, treat and use the methane in the LFG as a fuel. This augments the reduction of GHG emissions since the methane potentially displaces alternative energy sources which may have GHG emissions associated with their production and use. The methane fuel can be used on-site or nearby the landfill for heating purposes, generation of electricity, in co-generation systems offering high energy-efficiency, or can be compressed for use as a transportation fuel. Another option is to combust the methane in a flare without using it as a fuel source at all. This option achieves a reduction of GHG emissions by converting the methane into carbon dioxide which has a lower GWP. Other approaches to reduce GHG emissions from landfills include reducing landfilling of waste, and undertaking aerobic landfill management practices. All of these and other options can be combined in developing a comprehensive strategy to achieve reductions in GHG emissions from landfills.

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[84] Hickling, Emcon Associates, "Options for Managing Emissions From Solid Waste Landfills", 1994, Prepared for Solid Waste Management Division and Air Issues Branch, EPS, Environment Canada.

A portion of the methane available in LFG is already being captured and oxidized to carbon dioxide. As of December 1995, there were approximately 25 to 30 landfill sites in Canada where LFG extraction systems have been installed, or were under construction. The amount of methane reduction has been estimated at 270 kilotonnes or 5,700 kilotonnes of CO_2-equivalents[84]. At nearly half of these sites, methane is collected and utilized as an energy source for heating purposes or for generation of electricity. At the other sites, the LFG is flared.

Most of the very large sites (landfills with greater than 8 million tonnes of waste capacity) already have gas collection and treatment facilities. There may be a few very large sites which have yet to install collection and treatment systems. A smaller percentage of medium sized landfills (between 2 and 8 million tonnes of waste capacity) have yet to install collection and treatment systems. It is estimated there may be between 30 and 100 sites across Canada in this category. A low portion (less than 5%) of the thousands of small sites (less than 2 million tonnes of waste capacity) across Canada have installed gas collection systems.

The business as usual scenario is that emissions from landfills will increase approximately 25% between the 1995 and 2010 (Environment Canada). This scenario assumes no waste diversion to composting or increase in recycling programs. Emissions are expected to increase in line with increases in human population.

6.3 Reduction Technologies

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[84] Hickling, Emcon Associates, "Options for Managing Emissions From Solid Waste Landfills", 1994, Prepared for Solid Waste Management Division and Air Issues Branch, EPS, Environment Canada.

Options for Reducing GHG From Landfills

- Flaring of methane (oxidation)
- Using methane as a fuel
    - For electricity generation
    - For electricity with co-generation
    - For methane supply into natural gas distribution systems
    - Compressed methane for transportation fuel
- Reduced waste generation and landfilling

6.3.1 Site Characterization

There are upwards of 10,000 landfill sites in Canada[85]. While some jurisdictions have information on landfill sites they manage, a comprehensive inventory of landfill sites in Canada has yet to be conducted. Such an inventory would be useful to identify and better characterize GHG emissions, and establish priorities for action plans in this area. It is possible to screen landfills for their potential to emit GHG and therefore their potential to collect methane for energy purposes. Factors which influence the attractiveness of a landfill site for installation of GHG reduction systems include:

- age of the site;
- status of the site (closed or operating);
- type of site (municipal solid waste, industrial, etc.);
- waste density;
- population served over time;
- size of the site (depth, area); and
- distance to nearest residential, industrial, commercial facilities.

Some of this information is available from municipalities and provincial governments which issue Certificate of Approvals (C of A) for landfill operations. A potential side benefit in developing a consolidated inventory may be the creation of a more comprehensive toxic substances site inventory.

Once a broad screening of sites has been carried out, an analysis of site specific factors is required. Each landfill site is somewhat unique, such that some analysis is needed to assess whether it is economically feasible to collect and utilize methane as an energy source, or whether

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[85] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, April 1997.

flaring or another reduction strategy is preferred. Some of the more important factors relating to the decision may include:

- rate of methane production;
- ability to contain methane;
- duration of methane production (life of the site);
- quality of the LFG stream (level of contaminants);
- market for energy; and
- other benefits of GHG reductions (e.g., reduction of odour problems).

The final factor, listed above, may in many cases be the most important. Approximately 80% of LFG extraction systems are installed to address nuisance odours. Sulphur containing substances such as hydrogen sulfide and mercaptans have a "rotten egg" fragrance and are the major contributors to odour problems. Some volatile organic compounds may also contribute to an odour problem for the surrounding community.

Beyond odour reduction there are other potential benefits of installing GHG reduction systems. Various substances typically contained in LFG and emitted to the atmosphere have been declared "toxic" under sections 11a, 11b or 11c, of the Canadian Environmental Protection Act (CEPA). These include vinyl chloride monomer (VCM), 1,2 dichloroethane (DCE), and dichloromethane (DCM). Some other emitted chemicals have been defined as ozone depleting substances which have been restricted or have been phased out of commercial use in Canada (i.e., 1-1-1 trichloroethane). Substances such as hexane, toluene and xylene are defined as volatile organic compound (VOC) precursors for ground level ozone formation.

Hazardous and Toxic Substances Contained in Landfill Gas

Substance	Primary Environment or Health Concern	Major Products of Combustion
Hydrogen sulphide (H_2S)	Odour	SO_2
Mercaptans	Odour	SO_2, CO_2
Vinyl chloride monomer (VCM)	CEPA toxic	CO_2, HCl
cis 1,2 dichloroethane (DCE)	CEPA toxic	CO_2, HCl
Dichloromethane (DCM)	CEPA toxic	CO_2, HCl
Hexane	VOC	CO_2
Toluene	VOC	CO_2
Xylenes	VOC	CO_2
Chloromethane	Ozone depleting substance	CO_2, HCl
1-1-1 trichloroethane	Ozone depleting substance	CO_2, HCl
Trichlorofluoromethane	Ozone depleting substance	CO_2, HCl, HF
Concentration in LFG	<4000 ppm	

Sources: CRA 1994, US EPA 1993, Environment Canada 1995

Before collection, treatment or electricity generation equipment is installed, a site specific feasibility study is required. These studies define the market (if fuel, steam or electricity are to be sold), operational, overall economic feasibility and environmental impacts of the investment.

6.3.2 Gas Collection and Treatment

Before methane in the landfill can be used as a fuel it must be collected and treated to remove particulates, water, corrosive compounds and other impurities.

Landfills (or celled portions of the landfill) are usually capped with an impermeable layer to prevent gas from escaping, and to prevent oxygen from infiltrating the landfill, thereby affecting the anaerobic methane-generating bacteria. Thick layers of soil, clay and synthetic polymeric geomembranes are used to create capping layers and retaining walls around the site. These precautions maximize the efficiency of the collection system.

Gas collection systems consist of drilled wells or horizontal trenches, interconnecting pipes and a compressor creating negative pressure on the system that ensures gas flows to a central collection point. The total system needs to be engineered taking into consideration site specific factors, such as the number of wells, their spatial location and the depth of specific landfill characteristics. For example, a well sealed system may require fewer wells since a greater pressure may be applied without concern of oxygen infiltration. Denser, less permeable refuse will require more closely spaced wells. The efficiency (recovery of methane versus that contained in site) of the system will vary depending on the design. While some well designed systems can achieve close to 100% efficiency, 70 to 80% is more typical. Gas can also be recovered from unsealed landfills with lower efficiency.[86]

6.3.3 Gas Treatment

As noted above, LFG is a mixture of methane, carbon dioxide and various impurities. Water, particulates and corrosive substance impurities need to be removed from the gas to minimize maintenance and operational problems with the collection and fuel using equipment. Carbon dioxide separation equipment can be used to increase the quality (heat content related to portion of methane) of the LFG.

Particulates can clog pumps or cause excessive wear. Filters and water scrubbers are the two primary treatment methods. Filters must be replaced as they build-up with a resultant increase in pressure drop. Although somewhat more complex, water scrubbers do not require the replacement of clogged filters.[87]

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[86] US EPA., "Options for Reducing Methane Emissions Internationally, Volume I: Technology Options for Reducing Methane Emissions, Report to Congress", July 1993.

[87] Ibid

Drainage water can easily be removed with traps at the well head. However, water vapour contained in the gas needs to be treated separately. Various technologies can be used including: condensation; glycol (usually ethylene glycol) treatment; and use of dry desiccants such as silica gel and activated alumina. Using dehydrating agents involves the regeneration of the active ingredients. In the case of glycol it is separated from the water using distillation, while dry desiccants can be regenerated by heating to evaporate the contained water. These technologies are well developed and have been employed in the natural gas production industry as well as many other industrial processes for many years.

Corrosive compounds contained in the gas or resulting from combustion can cause long term damage to collection and fuel using systems (i.e., generators). Sulphur and chlorine containing compounds can form sulphuric acid and hydrochloric acid (as well as toxic substances) which degrade equipment over time. Sulphur compounds can be removed with activated carbon filters or absorption onto iron oxide or other media. Hydrocarbons, chlorinated or otherwise, can be removed with condensers (some may be removed in the process of condensing water vapour), activated carbon filters or solvent treatment.

If the methane content of the LFG needs to be increased to enhance the quality of the fuel, carbon dioxide separation technology may need to be applied. Removing carbon dioxide from the gas is typically not undertaken mostly due to expensive carbon dioxide separation technologies. Carbon dioxide separation technologies including amine scrubbing, pressure swing absorption (PSA), molecular membranes and sieves are available. However, their broader applicability to landfill gases requires research and development to lower their costs.

Landfill Gas Treatment Systems

Main separations features In addition to separating carbon dioxide and methane	Process Examples	Mechanism	Capital Costs	Annualized Capital + Operating Costs	Annualized costs (3 mmscfd gas flow)	Annualized costs (1.5 mmscfd gas flow)
			($million)	($million)	($/$CO_2$-eq)*	($/$CO_2$-eq)*
Can remove H_2S	Girbotol	Absorption Using amine-MEA Steam stripping	$2.2	$0.6	$4.0	$8.1
Can remove H_2S	SNPA	Absorption Using amine-DEA Steam stripping	$1.5	$0.4	$2.2	$5.5
Water and water soluble components	DRIZO	Absorption Using glycol-TEG	$1.4	$0.2	$1.9	$2.8
Water & soluble contaminants	BINAX	Absorption with water	$3.6	$0.9	$6.4	$12.8
Can remove organic hydrocarbons and H_2S	Selexol	Absorption Using dimethyl ether of propylene gycol (solvent)	$1.2	$0.3	$2.3	$4.6
Requires gas pretreatment	PSA	Pressure swing adsorption				
Effective for CO_2, less effective for H_2S	Membrane	Porous polymeric membranes	$1.1	$0.3	$2.1	$4.2

Source: [88]. * Excludes GWP reduction credits associated with displacement of other fuels.

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[88] Fouda, A., et al, "Landfill Gas Treatment - Existing Technologies and Economics of Fuel Quality Gas Production", Institute for Chemical Process and Environmental Technology, National Research Council of Canada, CANMET. Prepared for Environment Canada, Hazardous Waste Branch, 1997.

6.3.4 Flaring

Flaring is a simple and low cost option to reduce methane emissions from landfills. This reduction option can achieve a high reduction in GWP since the methane, which has a GWP of 21, is oxidized to carbon dioxide with a GWP of 1. The efficiency of the flare system can reach as high as 98% methane control. A disadvantage of this system is that the methane is not used as a fuel. Flaring can be used as a stand-alone control option or as a back-up with energy recovery systems. Energy recovery systems which cannot fully utilize the methane fuel may need to flare the stream intermittently.

Flaring can occur in an open or closed flare. Closed flaring systems offer better control of air (oxygen) and gas flow to maximize the efficiency of the combustion process and achieve the greatest GHG reduction. Closed flaring is aesthetically preferred, and can be more easily maintained and tested for operating efficiency and emissions. However, the cost of an open flaring system can be 5 to 10 times less than closed units.

Estimated Capital and Operating Costs For Flaring Systems

(order-of-magnitude estimates only - will vary substantially site to site)

Landfill capacity	Capital Costs	Annualized Capital	Annual Operating	Total Annualized Costs
Less then 2 million tonnes	$100,000	$20,000	$3,000	$23,000
Between 2 and 8	$150,000	$23,000	$4,600	$27,600
Greater than 8	$200,000	$35,000	$7,000	$42,000

Based on cost equations developed by U.S. EPA[89], and simplifying assumptions on methane flow rate from landfills.
Exclude collection system.

On a weight basis, the GHG reduction level possible with flaring systems is 87% of the methane oxidized. (Carbon dioxide generated from oxidizing methane lowers the GHG reduction potential). The reduction efficiency of the process is also affected by the capture efficiency of the LFG. This may lower overall GHG reduction to approximately 30 to 70% for a particular site, and will be influenced by the design of the gas containment and collection systems.

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[89] Hickling, Emcon Associates, "Options for Managing Emissions From Solid Waste Landfills", 1994, Prepared for Solid Waste Management Division and Air Issues Branch, EPS, Environment Canada.

6.3.5 Methane Utilization

The methane stream collected from landfill gas can be used as an energy source for applications as:

- electricity generation;
- co-generation of steam and electricity;
- supply into natural gas distribution systems for heating; and
- compressed methane for transportation fuel.

The larger landfill sites in Canada are more likely to have installed electricity generating equipment. Medium sized facilities tend to utilize the LFG for heating, often selling to a nearby industrial user. In many cases, these landfills have the option of flaring the LFG if customer requirements are less than the generation rate. Smaller facilities, generally with lower rates of production merely flare the LFG, without any energy recovery. Approximately 40% of the landfills with collection systems operated flaring systems only in Canada in 1995. In conducting this study, no landfill sites operating in Canada were identified to be compressing and selling methane for transportation fuel. However, some landfills in the United States, collect, compress and sell methane from LFG to fleet vehicles.

Number of Sites in Canada With LFG Utilization

	1995	**%**
Electricity*	5	20%
Heating*	11	40%
Flaring only	11	40%
Total	27	100%

* Flaring may also be carried out.
Some heating applications not identified.

6.3.5.1 Electricity and Steam Generation

Electrical generation costs depend on the equipment used and the amount of power the system is designed to produce. Larger landfills have the advantage of better economies of scale and the use of more efficient processes for lower capital costs per unit of electrical energy produced. Many possible system sizes can be installed. Electricity generating systems require a market for the power. Long term contracts with utility companies or industrial customers are required to ensure markets for the power.

A 5 to 6 MW reciprocating engine driving a generator can be operated with a LFG stream of 2.5 to 3 mmscfd containing 50% methane by volume. The installed capital costs of this size of system is approximately $7 to 10 million. There are examples of landfill sites in Canada where these systems have been installed. One such system has been installed by BFI at the Lachenaie Landfill in Quebec. BFI owns and operates the landfill. The system includes gas treatment and use of the gas stream in four reciprocating engines. Each engine drives a 1 MW generator. A 25 year contract for selling the power has been signed with Hydro-Quebec.

Another example is the Beare Road Landfill Site in Scarborough, Ontario. The landfill is owned and operated by the Municipality of Metropolitan Toronto. The power generating system has a capacity of 5.6 MW of power and features seven Caterpillar 3516 engine generator sets. The capital cost of the system in 1996 was $8.7 million. Ontario Hydro has contracted to purchase 5 MW at 6.12 cents during the first 10 years of the contract. Metro Toronto receives royalties from the sale.

A system with a generating capacity of 20 to 30 MW would require upwards of $ 15 to 35 million in capital. There are several such systems operating in Canada. One has been constructed at the Brock West Landfill Site for $26 million in 1990[90]. The power is sold to Ontario-Hydro. This facility only has a knock-out tank system for reducing water (and dissolved components) content of the gas. Methane and carbon dioxide are not separated from the nitrogen, oxygen and other minor gas components in the stream.

Another system is at the Keele Valley Landfill Site in Vaughan, Ontario. That system features a power plant with two boilers, two gas-turbine generator sets, an exhaust gas-boiler with supplemental firing, and a large steam-turbine generator set. The system has an electrical generating capacity for 30 MW. The capital costs were approximately $17 million in 1995. Natural gas can be used as supplementary fuel if required. Ontario Hydro has agreed to purchase the power, with royalties being paid the municipality. Eastern Power of Mississauga, ON owns and operates the steam and electrical generating plant. Similar to Brock West, this facility does not separate the carbon dioxide, methane, nitrogen, oxygen and other minor gas components in the stream. Only the water which condenses in knock-out tanks is removed from the stream.

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[90] Fouda, A., et al, "Landfill Gas Treatment - Existing Technologies and Economics of Fuel Quality Gas Production", Institute for Chemical Process and Environmental Technology, National Research Council of Canada, CANMET. Prepared for Environment Canada, Hazardous Waste Branch, 1997.

Typical Composition of LFG at Keele Valley

Component	Gas Composition (volume%)
Methane	47%
Carbon dioxide	37%
Nitrogen	13%
Oxygen	2%
All other	1%
Total	100%

Source: Lou Ciardullo, Senior Engineer, Keele Valley

6.3.5.2 Fuel To Nearby Users

The LFG stream may be used as a source of methane for heating purposes. Approximately 11, or 40% of the landfills collecting LFG, treat and route the stream to nearby customers. This utilization is feasible when the distance between the landfill and the customer is short such that the pipeline and compression costs for delivery are not high.

Identified Customers for Methane From Specific Landfills

Landfill	Location	Major Customer
Port Mann	Surrey, BC	Domtar gypsum plant
Richmond	Richmond, BC	LaFarge Canada Cement
Coquitlam	Coquitlam, BC	Newstech (paper deinking plant)
Jackman	Langley, BC	Greenhouse
Tretheway	Matsqui, BC	Building heat
Ottawa Street	Kitchener, ON	Cement kiln

The cost of treatment and transportation systems to nearby customers will be strongly influenced by the quantity of the gas flow and the distance to the end-user. Pipeline construction costs have been estimated at $425,000/km for a polymeric pipe at 100 psi. Total investment to handle a 7.6 mmscfd LFG flow including a 5 km pipeline has been estimated to require a capital cost of $6.0 million. A system requiring a 10 km pipeline would cost nearly $8 million. Revenues from the sale of the gas from these size of systems can generate a positive return on investment ranging from 10 to 21%[91].

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[91] Ibid

6.3.5.3 Reduced waste generation and landfilling

Reducing waste can reduce the amount of methane emitted from landfills. There are several general approaches to achieving lower waste generation and landfilling. One approach is to increase the recycling of waste products that generate methane during anaerobic degradation in landfills. This is a complex approach requiring broad societal (households and product manufacturers) education and cooperation. Another approach is to increase the use of alternative disposal methods, such as aerobic composting and waste incineration (which may produce CO_2 but lesser quantities of methane).

6.4 R&D Capabilities and Requirements

Collecting, treating, extracting, transporting and utilizing LFG for production of electricity or fuel is underpinned by a broad set of technologies, most of which have been developed and are being applied in the field for large or medium landfill sites. However, smaller landfills present cost issues and therefore opportunities for technology improvement. At the same time, the basic technology for each component of the landfill gas systems continues to evolve.

The business of selling products and services in support of LFG collection and utilization brings various suppliers together. However, companies engaged in conducting technology research and development are typically not solely dedicated to the LFG business system, especially in Canada, where the demand for new systems is limited.

Research and development covering technologies in this field are not typically aimed directly at addressing emissions from landfill gas. Many of the firms involved have R&D activities to provide products and services to a broader market. Some of the companies involved in selling equipment to the LFG development industry, have a base of business in natural gas development, in Western Canada as well as other gas producing regions. Enerflex Inc. based in Calgary, AB is an example. The company provides products and services to the natural gas production and distribution industry. However, even this company which has annual sales in the $300 million range, does not design or make its own generators and compressors. The firm, like others in Canada, distribute products designed and manufactured in the United States, Japan or Europe. Caterpillar, and Waukesha based in Wisconsin are two suppliers of generators and compressors which are typically used at landfills sites. Canadian suppliers tend to customize, distribute and service the equipment for the regional markets.

Major LFG System Component Suppliers and Technology Platforms

Types of Firms	Technology Platform	Example firms
Engineering firms	Site assessments, custom design, engineering, project management	Gore & Storie, Conestoga Rovers (CRA), E.H. Hanson, SNC, Eastern Power Developers
Site Developers	Site development, financing, operations	E.H. Hanson, SNC, Eastern Power Developers
Gas treatment	Absorption, Glycol dehydration Solvent absorption Membrane systems	Chemical suppliers (Dow, Union Carbide) Gas suppliers (Praxair)
Compressors, Electrical generators, Blowers	Compressor & engine fabrication, design and customization, equipment controls	Caterpillar, Enerflex Power, Toromont, Ariel Compressors, BTB, Ingersol-Rand, Harber Detroit

6.5 GHG Reduction Costs

There are many possible cost scenarios related to reducing GHG emissions from landfills. In addition, the actual costs for each site can only be determined after close examination of the quality and flow rate of the gas, the size of the landfill, gas utilization equipment to be used and many other site specific considerations. The costs presented here therefore should be used as order-of-magnitude only and serve the purpose of identifying the nature of the problem and resources required to achieve various levels of GHG reduction from landfills.

The capital cost of achieving a 20 to 30% reduction in GHG emissions from landfills by flaring the methane gas is estimated at approximately $10 million. This low capital cost option would entail installation of capture, collection and flaring systems at the largest 60, or so, sites which have yet to install systems. This estimate excludes site identification and assessment costs. The estimate uses simplifying assumptions and is based on previous investigations of the number of landfills and the emissions from different sizes of landfills in Canada[92,93,94].

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[92] MacViro Consultants Inc. in Association with AEI/ALCO, "An Action Plan for Energy Recovery From Landfill Gas in Ontario", Ministry of Energy, Queen's Park Toronto, ON, January 1991

[93] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, April 1997.

Alternatively to flaring, the largest sites in Canada emitting the greatest amounts of methane may be suitable for using the methane for energy production. Generation of electricity increases the capital cost to approximately $350 million, but offers a net annualized net benefit of nearly $30 million. The sale of electricity more than offsets the cost of capital and annual operating costs.

The cost of achieving an additional 10 to 20% reduction (i.e., 30 to 40% total reduction) in GHG emissions from landfill sites needs to address the many small sites which produce low (or no) amount of methane. The capital costs to install collection and flaring systems at thousands of small facilities is roughly estimated at $800 million in capital, or $186 million on an annualized basis.

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94 Waste Disposal Branch Ontario Ministry of the Environment, "Waste Disposal Site Inventory", Queen's Printer for Ontario, June 1991.

Flaring Only: Not Electricity Generation

Size of Landfill (million tonnes of waste)	Estimated Number of Landfills in Canada	Potential to Control (@ 65% capture & 83% destruction efficiency#)	Total Capital Capital Cost For All Sites	Total Annualized Capital plus Operating	Total Annualized Unit Capital plus Operating Costs
		(Mt-CO_2-eq)	($ million)	($ million)	($/t-$CO_2$-eq)
Small (less than 2)	8,000	2.6	$800	$184	$71
Medium (2 to 8)	50	3.7	$7.5	$1.4	$0.4
Large (greater than 8)	10	1.2	$2.0	$0.4	$0.3
Total / overall*	8,060	7.50 (41%)	$809.5	$185.8	~$25

Cost information sources: [95][96], Industry sources operating landfills.

83% efficiency = 87% theoretical * 95% destruction efficiency in flare. Theoretical reflects production of CO_2 resulting from oxidation of methane.

Flaring For Small Sites, Electricity Generation at Medium and Large Sites

Size of Landfill (million tonnes of waste)	Estimated Number of Landfills in Canada	Potential to Control (@ 65% capture & 83% efficiency)	Total Capital Capital Cost For All Sites	Total Annualized Capital plus Operating	Revenues From Sale of Electricity	Net Annualized Costs (Benefits)	Net Unit Annualized Costs (Benefits
		(Mt-CO_2-eq)	($ million)	($ million)			($/t-$CO_2$-eq)
Small (less than 2) (All Flaring)	8,000	2.6	$800	$184	0	$184	$71
Medium (2 to 8) (Electricity)	50	3.7	$250	$90	$105	($15)	($4)
Large (greater than 8) (Electricity)	10	1.2	$100	$28	$42	($14)	($12)
Total / overall*	8,060	7.50 (41%)	$1,150	$260	$147	$155	~$21

Major assumptions:Capital requirements $1 million per 1 MW electricity generating capacity (complete system installed). Capital annualized over 20 year at 10% interest rate. Price of electricity: 5 cents/kWh

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[95] MacViro Consultants Inc. in Association with AEI/ALCO, "An Action Plan for Energy Recovery From Landfill Gas in Ontario" , Ministry of Energy, Queen's Park Toronto, ON, January 1991

[96] Hickling, Emcon Associates, "Options for Managing Emissions From Solid Waste Landfills", 1994, Prepared for Solid Waste Management Division and Air Issues Branch, EPS, Environment Canada.

6.6 Recommendations

A strategy to maximize reductions in GHG emissions at minimal cost or with financial benefits needs to address the largest sites which generate the greatest quantities of emissions first. At the same time companies coordinating the installation of landfill gas utilization systems point out that the cost of government approvals make the systems more expensive. Their recommendation is to streamline the approval process for such systems.

Implementing a process to achieve reductions in GHG emissions from landfill sites requires collaboration between federal and provincial governments as well as local municipalities. This collaboration may need to be initiated and led by Environment Canada, which has an interest in achieving GHG reduction targets. Provincial governments and local municipalities typically have greater interest in addressing hazardous situations (presented through LFG migration), or reacting to odour problems caused by landfills. Most (>80%) of the very large landfills that have warranted investment in collection and gas utilization systems for energy, have already been exploited. Provincial and municipal resources are not likely to be committed to address GHG emissions, where energy savings are not present. However, some municipalities may be overlooking medium or large landfill sites which present an opportunity for LFG utilization.

Components of the GHG emission reduction process that requires development include the following:

- identify and focus on remaining medium and large sites;
- assess feasibility of sites with potential for LFG utilization and encourage direct use;
- support development of technologies and practices that increase capture and collection efficiency, and reduce costs for all landfills; and
- streamlining municipal and provincial approvals process for installation of new systems.

Industry participants indicate any technology development that lowers costs of capture, collection, treatment, monitoring and methane utilization equipment for medium and smaller facilities would be beneficial in dealing with the broad problem of emissions from many small landfills.

Capture technology has evolved over the years such that the portion of methane collected versus emitted has increased. However, with capture rates in the 50 to 70% range, improvements are possible. Landfill design, equipment improvements and better monitoring practices can achieve positive results to increase the portion of methane that is captured. Improved separation translates into improved energy efficiency for utilization equipment, improved environment effects, and longer system durability. Sulphur and chlorine containing compounds can contribute to the formation of acids (sulphuric and hydrochloric) which reduce the durability and performance of equipment.

7. Adipic Acid Production

7.1 Summary

A significant reduction of nitrous oxide (N_2O) from adipic acid production has already occurred through the development and installation of a catalytic reduction technology for the only adipic acid plant in Canada. An estimated 30 kt/yr of N_2O emissions (9,300 kt-CO_2 equivalent) have been reduced from 1995 levels of 35 kt/yr for a total capital cost of about $15 million. On an annualized basis, the cost of reduction is calculated as $0.2 per tonne of CO_2 equivalent reduced.

This section summarizes the adipic acid situation as a case study in the successful development and application of technology to reduce greenhouse gas emissions.

7.2 Background

Nitrous oxide is a significant by-product from the production of adipic acid. Adipic acid [$COOH(CH_2)_4COOH$], a 6-carbon dibasic acid, is an important chemical intermediate used in the manufacture of nylon fibres and resins, plasticizers and other plastics.

In Canada, only the DuPont Canada plant at Maitland, ON produces adipic acid. This plant is one of three that DuPont operates in North America and it represents about 15% of total North American production. North American adipic acid production represents about 45% of worldwide production.

Adipic Acid Plants in North America

Company	Location	Capacity (kt/yr)
DuPont	Victoria, TX	318
Solutia (formerly Monsanto)	Pensacola, FL	273
DuPont	Orange, TX	181
DuPont Canada Ltd.	**Maitland, ON**	**136**
Allied-Signal	Hopewell, VA	~90
Total		998
Global Production		~2,200

Source: Chemical Marketing Reporter

The majority of the adipic acid produced in Maitland is sent to DuPont's Kingston, ON nylon plant, where it is reacted with hexamethylenediamine [$NH_2(CH_2)_6NH_2$], a 6-carbon diamine, to produce nylon 6/6, the most common polymer in the nylon family[97]. At Kingston, bulked continuous filament (BCF) nylon is produced for carpets and other textiles. The remaining adipic acid is exported to the US, mostly to other DuPont nylon plants.

Adipic acid is produced by a two-step oxidation of the raw material, cyclohexane (C_6H_{12}). Nitrous oxide is generated as a by-product in the second step of this oxidation process. In the first step, cyclohexane is oxidized with air in the presence of a cobalt catalyst to a mixture of cyclohexanol (an alcohol) and cyclohexanone (a ketone). In the second step, the cyclohexanol-cyclohexanone mixture is further oxidized by a 50-60% nitric acid solution containing a catalyst of vanadium and copper. Nitrous oxide is stripped from the oxidation mass and exits the process as a gas stream. The amount of nitrous oxide generated in the nitric acid oxidation reaction is substantial, up to 30% of the adipic acid production volume. Roughly 35 kt/yr of N_2O is produced as a by-product from production of about 112 kt/yr of adipic acid at Maitland.

7.3 Emissions and Trends

From 1990 to 1995, the estimated level of nitrous oxide emissions from DuPont's adipic acid production in Maitland has ranged from 29 to 35 kt/yr. The level stayed at about 35 kt for 1994 and 1995 and was expected to remain at about this level for 1996. DuPont has estimated that this level (35 kt) accounts for some 31% of Canada's anthropogenic sources of nitrous oxide, based on government estimates[98]. Using a 100-year Global Warming Potential factor of 310 for nitrous oxide, this amount of nitrous oxide emissions is equivalent to about 11,000 kt of carbon dioxide.

Nitrous Oxide Emissions (1992-2000)

	1990	1991	1992	1993	1994	1995	2000
N_2O Emissions (kt)	34.6	32.3	32.1	29.3	35.4	34.6	5.0
N_2O Emissions (CO_2 Eq kt)	10718	10000	9951	9080	10968	10726	1550
Adipic Acid Production (kt)	97.4	103.4	107.0	98.0	118.0	111.5	136.4
N_20/Adipic Acid Ratio	0.35	0.31	0.30	0.30	0.30	0.31	0.04

Source: DuPont Canada, VCR Progress Report, Sep. 24, 1996
CO_2 Equivalent calculated using N_2O GWP Factor of 310.

In August 1997, DuPont started up a catalytic abatement installation (CAI) to treat the emitted nitrous oxide stream. The planned reduction in nitrous oxide emissions is about 80-90% in the first year of operation (1997) with higher levels of utilization expected in the second and third

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[97] Each 6 refers to the number of carbons in the diamine and the dibasic acid respectively.

[98] DuPont Canada Ltd. original VCR submission, Dec. 19, 1994

years. After 1997, this reduction will have the effect of reducing nitrous oxide emission levels from adipic acid production to about 5 kt/yr or about 1500 kt/yr of CO_2 equivalent.

7.4 Technologies to Reduce Emissions

There are two possible treatments of nitrous oxide emissions from adipic acid production plants. The first is the conversion of nitrous oxide back to nitric acid (oxidation). The second is its catalytic reduction to inert nitrogen and oxygen gases. The second method was selected by DuPont for all three of its North American adipic acid plants and is described below. No information applicable to adipic acid plants was found for the first treatment method.

7.4.1 Catalytic Reduction of Nitrous Oxide

The DuPont catalytic reduction installation uses a catalyst specifically designed for N_2O reduction at specified operating conditions. The catalyst technology is new, developed for DuPont in the early 1990's by Engelhard, a leading catalyst and pollution control technology supplier. According to Engelhard, there are only a few catalysts currently on the market specifically targeted for nitrous oxide. The catalyst is thought to use zirconia on a zeolite[99] structure for selectivity.

DuPont, which uses a number of NOx reduction technologies from Engelhard, requested a catalyst that could target nitrous oxide and also reduce trace amounts of carbon monoxide and hydrocarbons, something that other NSCR catalysts could not do well. Engelhard screened a number of catalysts and submitted one to DuPont for consideration. Once qualified, it was tested on a pilot scale at the Victoria, TX plant. The first DuPont abatement unit was installed in Orange, TX in early 1997. The Maitland, ON plant unit started up in August 1997 and the Victoria, TX unit started up recently. A number of research papers were published during this development process and presented at forums.

DuPont summarizes their success with nitrous oxide reduction as follows:

> "In DuPont's search for a technology to deal with N_2O, the first choice was conversion of this gas to nitric acid (an important raw material in making adipic acid, which is used to manufacture nylon). This route, however, was unproven and too risky, and has been shelved in favour of a demonstrated process to catalytically convert nitrous oxide into nitrogen and oxygen. We have authorized spending approximately $15 million to the design and installation of this abatement technology. Construction is underway and we expect our facility to be operational by mid-1997.

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[99] Zeolite: an alumina silicate matrix having a unique lattice structure and specific acid sites

> "Our goal is to abate 80% of nitrous oxide within 2 years of start-up. While this project will recover some energy from the exothermic reaction to reduce nitrous oxide, the investment will not yield any usable products for DuPont. Over the longer period, we hope to achieve up to 95 per cent abatement, so that by the year 2000 and beyond, we will achieve more than our earlier commitments."
>
> It should be noted, however, that business growth will result in higher production levels of adipic acid, so that the 95 per cent abatement will show growing levels of nitrous oxide after 1998-99. [100]"

DuPont reports that the installation is operating well and currently meeting expectations. The abatement technology is reported to have a reduction efficiency percentage "in the high 90's" when operating steadily. Since the unit has only recently started up, there has been occasional downtime. For example, the abatement unit cannot operate during the occasional startup and shutdown sequences of the adipic acid plant. Other mechanical problems also require short term shutdowns for maintenance. With continued learning curve experience, DuPont intends to increase the operational "up-time" above 90% in future years[101].

Since this unit has started up and is running at greater than 95% efficiency about 90% of the time, it will have achieved a reduction of about 30 kt/yr of nitrous oxide emissions from 1995 levels. Using a GWP factor of 310 for nitrous oxide, this reduction is equivalent to about 9,300 kt of CO_2, or roughly 9% of total Canadian greenhouse gas emissions from non-energy sources.

In 1994, the cost of design, purchase and installation of DuPont's catalytic abatement installation was estimated at $15 million. A recent estimate by plant personnel was $15.3 million. The cost of the catalyst charge for this unit probably did not exceed $1 million. The catalyst lifetime is not known, but is assumed to be five years.

The $15.3 million cost, amortized at 10% over 20 years is equivalent to an annual cost of $1.8 million/yr. Adding the assumed cost of a new catalyst purchase every 5 years would bring total annualized cost levels to $2.0 million/yr. The cost per tonne reduced is calculated at about $67 per tonne N_2O reduced or $0.2 per tonne of CO_2 equivalent reduced. Besides the additional energy credits associated with an exothermic reaction, no direct benefits or credits to DuPont have been identified by using this process.

The theory of how to increase the control efficiency of catalytic reduction technology was addressed by Engelhard. In a broad sense, catalysts behave like constant reduction percentage media. For relatively simple reactions with controlled operating conditions, if a volume of catalyst achieves a 90% reduction, then twice the catalyst volume should achieve a 99%

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[100] DuPont Canada Ltd., VCR Progress Report, Sep. 24, 1996.

[101] DuPont Canada Ltd., Steve Lauridsen, conversation Feb. 20, 1998

reduction. It is technically feasible to achieve higher reductions on virtually all pollutant levels, but the law of diminishing economic returns applies as costs per tonne increase exponentially. DuPont has designed this unit to achieve a high reduction efficiency, and according to DuPont it would be economically prohibitive to retrofit the unit to achieve greater levels of reduction efficiency.

In the absence of specific regulations, the reduction levels followed a progressive evolutionary trend. The design of a control system involves economic decisions as to what is the appropriate level of reduction in $/t terms. In the US, companies using Reasonably Available Control Technology (RACT) calculate the $/t levels according to prevailing industry-wide benchmarks. However, efficiency gains and competition serve to raise the bar to higher reduction levels over time.

7.5 R&D Capabilities and Requirements

DuPont's technology for the nitrous oxide catalytic abatement installation is the property of E.I. DuPont De Nemours, based in the United States. Their corporate head office and research centre is located in Wilmington, DE. Engelhard Process Emissions Systems is known to have been involved in the development process, working closely with DuPont. Their corporate office and research centre are based in Iselin, NJ. Most research took place at these two centres or at the Victoria, TX plant, where a pilot unit was set up. No significant research for this process occurred in Canada.

DuPont conferred with other global producers about technologies to reduce N_2O emissions a few years ago. Monsanto (now Solutia) opted out of working with DuPont, since they already had an abatement unit installed at their Pensacola, FL facility. Other adipic acid producers have developed their own technologies. Beyond installations at new DuPont plants (a new adipic acid plant just started up in Singapore in Dec. 1997), there appears to be little opportunity for technology transfer for processes involving high N_2O concentrations.

Engelhard Corporation is a leading catalyst control technology supplier based in Iselin, NJ. The company invented the monolithic catalytic converter which forms the basis of current forms of automotive emission (particularly NOx) control. It also invented Selective Catalytic Reduction which has become the standard technology for controlling NOx emissions from industrial processes.

7.6 Recommendations

Since the technology has already been implemented to achieve significant GHG reductions in the only facility in Canada, there is little development potential for technology to reduce emissions further. Nevertheless, DuPont expects to achieve increased N_2O reduction levels with improved operating practices over time.

Broader application of this catalyst technology would involve facilities where the N_2O-emitting stream to be treated possessed similar characteristics to that presented by adipic acid plants. Research may be required to identify other Canadian situations and global customers for this type of technology, despite its limited potential. Potential customers may require scaled-downed versions of the niche technology.

Research and development in this area should be conducted in cooperation with DuPont which may hold patents on key features of the technology. DuPont Canada has been quite active in technology development and transfer opportunities. They may have interest in working with government to develop the market for this technology.

8. Lime Production

8.1 Summary

This section deals with technologies addressing process emissions of carbon dioxide from lime kilns. Lime kilns are found at cement plants, kraft pulp mills, and iron and steel facilities which use lime internally. There are also producers of lime selling to these industrial sectors as well as a broader merchant market.

Process Emissions From Lime Production

	1995 ($kT-CO_2$)	
Cement plants#	5,360	54%
Pulp and paper industry*	2,600	26%
Merchant lime production#+	1,990	20%
Total	9,950	100%

Source: * CHEMinfo Services estimates. Includes estimates of CO_2 captured and routed to precipitated calcium carbonate (paper fillers) production at pulp and paper mills.
Environment Canada - Jaques, et al
+ Includes production at iron and steel and other producers which use lime in their own processes as well as to sell to the merchant market.

Carbon dioxide dissociated from calcium carbonate during heating is inherent in the reaction. Although some of the carbon dioxide from lime kilns can be used internally, most kilns have no alternative disposition of the carbon dioxide. Therefore, this analysis of technology options considers areas for reducing emissions from lime kilns through different approaches. One relates to technologies that addresses emissions through reductions in lime consumption in major applications, such as cement, iron and steel, and pulp and paper. The second approach is to control carbon dioxide emissions with the installation of capture, treatment and extraction equipment. The extracted carbon dioxide would then need to be sequestered or stored in reservoirs to prevent releases to air.

8.1.1 Research and Development Requirements

Many areas need research and development support with respect to carbon dioxide emissions from lime kilns. The reason is that there are limited feasible options for major reductions of carbon dioxide at lime kilns. In addition, lime requirements are practically fundamental in some of the application areas, such as pulp and paper, iron and steel, and cement production. The lime industry itself and some markets relying on lime are technologically mature, such that the new challenge of reducing GHG emissions presents uncertainty with respect to required technology innovation. Some of the technology solutions need to come from a broad view of the industry encompassing lime applications. Areas for development identified in this analysis therefore include reduction in lime requirements in application markets, as well as developing a better understanding of control and sequestering of carbon dioxide that could be captured and extracted directly from lime kilns. Specific R&D areas for consideration include:

- substitutes, such as fly ash or slags, for clinker in cement;
- pulp and paper mill changes that reduce and use carbon dioxide;
- separation technologies at lime kiln operators; and
- sequestering technologies and carbonates (or other) product development.

8.1.2 Costs to Reduce

There are many possible technology adoption scenarios on which to base development costs for GHG reduction. This brief analysis considers the option of capture and extraction at lime kilns to provide an order-of-magnitude estimate for comparison purposes only. Under this scenario, unless the carbon dioxide can be sequestered (e.g., in carbonates), underground storage in soil or aquifers will be necessary. The control technology assumed for application to lime kilns is a pressure swing adsorption (PSA) or vacuum PSA units. It is assumed that this option will achieve a 60 to 80% GHG reduction. The level of reduction is compromised since GHG emissions will result from operation of the control, transportation and distribution systems.

Cost Summary for Lime Kiln Emissions

Activity Information and Costs	
Number of lime facilities in Canada	82
Carbon dioxide emissions (tonnes)	9,950,000
Total capital costs ($ million)	$200 to 300
Annualized (@ 10%, over 20 years) capital unit costs ($/tonne-$CO_2$)	$2 to $4
Variable costs ($/tonne-$CO_2$)	$20 to 50
Disposal costs for underground storage ($/tonne-$CO_2$)*	$115
Total cost range ($/tonne-$CO_2$)	$137 to $169
Associated carbon dioxide reduction	60 to 80%

* From Section 15: "Underground Storage - Enhanced Oil Recovery"

Total capital costs for installing PSA units at all lime kilns in Canada would be approximately \$200 to \$300 million or approximately \$2 to \$4 million per production site. Annualized at 10% interest over a 20 year term, these capital costs range from 2 to 4 \$/tonne-CO_2-reduced. Variable operating costs of \$20 to \$50 per tonne-CO_2 are assumed (based on industry experience with PSA operations), and will vary depending the carbon dioxide concentration of the kiln gas. These costs need to be added to sequestering or disposal costs. In this analysis, underground storage costs have been assumed at \$115 per tonne-CO_2 and are derived from analysis conducted for capturing and transporting CO_2 for underground injection in Western Canada (see Section 15). Therefore, the total costs to achieve a 60 to 80% reduction in lime kiln emissions range from approximately \$137 to \$169 per tonne.

These costs are high, providing strong incentive for stakeholders to seek and develop many other possible solutions to reduce the consumption of lime and associated emissions from lime production. One option is the substitution of fly ash for clinker in cement formulation. Although there would be research and development, and administrative costs associated with changing cement and concrete product quality standards, this option provides a potential net benefit for cement producers, since fly ash waste is less expensive than the clinker production costs. Therefore, a 5 to 10% reduction (versus total lime industry emissions) can be achieved at costs or with net benefits much less than those estimated above.

8.2 Emissions From Lime Production

Lime is a manufactured product composed of calcium oxide which is derived by calcining (heating) limestone, a natural sedimentary rock containing calcium carbonate and some magnesium carbonate. The term lime encompasses: quicklime (pure CaO); hydrated lime ($Ca(OH)_2$ with 24% contained water); and dead burned refractory dolomite lime (containing magnesium). Some lime, such as that sold to steel mills, is produced in pebble form. Lime is also regenerated (from calcium carbonate) for captive use at chemical kraft pulp mills. Lime is manufactured in various types of kilns involving the following chemical reactions:

$$CaCO_3 + \text{heat} \rightarrow CO_2 + CaO \text{ (high calcium lime)}$$

$$CaCO_3 \cdot MgCO_3 + \text{heat} \rightarrow 2CO_2 + CaO \cdot MgO \text{ (dolomitic lime)}$$

Substantial quantities of CO_2 are generated through calcining of limestone or other calcareous material. This calcining process thermally decomposes $CaCO_3$ to CaO and CO_2. The CO_2 concentration of the gas stream leaving the lime kiln typically ranges from 10 to 20% on a volume basis. The other major gas component is nitrogen (80 volume%). There are also minor amounts of oxygen and even lesser quantities of other oxides. Particulate matter is also entrained in the gas. In many cases, lime kilns are equipped with water scrubbers or electrostatic precipitators to reduce emissions of fine particulates (largely composed of calcium carbonate).

Typically, a low concentration (10 to 20%) of CO_2 in the gas stream makes capture and extraction of the dioxide problematic. Some kiln operators requiring CO_2 from the process in separate operations can achieve kiln gas concentration with 40% CO_2. The capital and variable operating costs to separate CO_2 (largely power) increases as the ratio of final concentration to starting concentration increases. Merchant carbon dioxide suppliers, who rely on chemical plants, ammonia facilities, crude oil refineries and other sources for higher purity carbon dioxide, have largely ignored lime kilns as a source for their needs.

8.3 Lime Production in Canada

There are at least 80 to 90 facilities in Canada where lime kilns are in operation. In Canada 20, or so, cement plants have kilns to provide lime for internal requirements. Similarly, lime kilns are present in practically every one of the 42 chemical kraft pulp mills in Canada. Pulp and paper mills also purchase lime to supplement on-site production. In addition to these and other captive producers of lime, there are merchant suppliers, some of which also make lime for their internal requirements. There are approximately 20 merchant lime producers in Canada. These producers sell lime to the pulp and paper, iron and steel industry, non-ferrous smelters, sugar refineries, waste water treatment, gas scrubbing and other miscellaneous uses.

Process Emissions From Lime Production

	Number of Facilities	1995	
		($kT-CO_2$)	
Cement plants[#]	20	5,360	54%
Pulp and paper industry*	42	2,600	26%
Merchant lime production[#+]	20	1,990	20%
Total	82	9,950	100%

Source: * CHEMinfo Services estimates. Includes estimates of CO_2 captured and routed to precipitated calcium carbonate (paper fillers) production at pulp and paper mills.
Environment Canada - Jaques, et al
+ Includes production at iron and steel and other producers which use lime in their own processes as well as sell to the merchant market.

Lime is an inexpensive solid chemical used throughout industry in a variety of functions. The largest end-use of lime is in the steel industry, where it is used as a fluxing material to remove impurities, adjust physical properties of steel, protect equipment from aggressive acidic materials and provide an artificial cover of slag on ladles.

In kraft wood pulp operations, lime is purchased to supplement onsite production which is required for regenerating pulping chemical. It is also used in paper production as a feedstock for precipitated calcium carbonate (PCC) production, a fine white filler. In construction, lime is often used for soil stabilization and asphalt paving. In water treatment, lime acts to precipitate "hardness" from water and provides a cheap alkali to adjust pH in wastewater.

Canadian Merchant Lime Consumption

Application	% Use
Iron and steel	50%
Pulp & paper*	10%
Construction	9%
Water treatment	9%
Sugar refineries	4%
All other uses	18%
Total	100%

* Includes precipitated calcium carbonate (PCC) production.
Excludes internal production of lime at pulp mill for causticizing.

The long term outlook for the Canadian lime industry is that it will grow at an average annual rate of 0 to 1%, less than the average annual growth rate over the last twenty years of 1.8%. Most of the growth will come from commercial sales, although the cement and pulp and paper industries will continue to increase their requirements slowly.

This analysis of technology options in this report considers areas for reducing emissions from lime kilns through different approaches. One relates to technologies that address emissions through reductions in lime consumption in major applications, such as pulp and paper, and cement[102]. The second approach is to address carbon dioxide emissions with the installation of capture, treatment and extraction equipment. The extracted carbon dioxide would then need to be sequestered or stored to prevent releases to air. Some sequestering options are described.

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[102] An analysis of technical options to reduce lime consumption in the steelmaking industry is quite complex and considered beyond the scope of this study, since there is a requirement to consider complex metallurgy and many components of the steel making process. Since steel producers are already practicing some lime reduction strategies (i.e., minimizing the presence of acidic silicon dioxide - SiO_2 - which is neutralized with lime). It also requires a benchmarking of the consumption of lime versus potential targets for each of the steel producers.]

8.4 Lime Use in Pulp and Paper Production

Paper production requires separation of wood fibres by chemical or mechanical means. Although each wood species is somewhat different in terms of its chemical constituents, cellulose, hemicellulose and lignins are wood components found in all species. Lignin can interfere with fibre bonding and result in a paper of lower strength, as well as one of low brightness and poor colour stability. It is preferred to retain cellulose and hemicellulose components for papermaking. Chemical methods involve treating wood fibres with various chemicals to remove lignin components. Mechanical methods separate wood fibres but leave constituents (i.e., lignins, cellulose, hemicellulose) intact within the fibres. Therefore, papers made from mechanical pulps contain lignin.

Chemical pulps are produced in the alkaline sulphate (kraft) process, acid or neutral sulphite process, or alkaline soda process. Kraft and sulphite pulps are used for fine printing papers, photographic papers and many other possible applications where high brightness and/or high strength are needed. Pulps made from the soda or neutral sulphite processes tend to be used for unbleached board products. Over 95% of the chemical pulps made in North America are kraft. Kraft pulps constitute approximately 65% of all pulps (including mechanical and deinked types). Many older, uneconomic acid sulphite mills have shut down over the last fifteen years. Mechanical mills have replaced some of the niche markets once satisfied by sulphite mills.

Mechanical pulps, made by thermomechanical (TMP), chemi-thermomechanical (CTMP) or stone groundwood pulping techniques are generally inferior in strength, brightness and other properties to pulps produced via chemical processes. Although technical developments have resulted in quality improvements, mechanical pulps are largely restricted to readily disposable applications, such as newspapers, directories and advertising insert flyers. Mechanical pulping techniques have a significantly higher yield (i.e. 95%) of fibre in relation to the quantity of wood used in the process, versus chemical pulps. By substantially reducing the lignin content in the fibre, kraft and other chemical pulping techniques result in a low yield (40 to 50% for kraft). Yield differences play a major role in the economics of production for each type of pulp. The yield also relates to the environmental impacts of pulp production. Close to 20 million metric tons, equivalent to nearly 55,000 metric tonnes per day, of mechanical pulps are available yearly from North American mills to papermakers on this continent and elsewhere. Two thirds of the production capacity is located in Canada, where there has long been a world-leading newsprint industry, largely a consequence of extensive stands of easily pulped softwoods and abundant electric power. Canada accounts for approximately one third of global mechanical pulp production.

8.4.1 Technology Trends in the Industry

Over the last decade there have been significant changes in technology adopted by North American chemical pulp mills, such that there are now a greater variety of commercially available processes and chemical agents used to delignify and brighten pulp. Many of the changes have come about as a result of environmental pressures on chemical pulp mills. The evolution of pulping and bleaching technology is expected to continue. Changes in application of chemicals and processes may include:

- increased use of oxygen for delignification of wood pulp;
- interest by some mills to make total chlorine free (TCF) pulp;
- increased use of ozone delignification;
- increased use of extended modified cooking (delignification) processes;
- increased use of enzymes and other delignification technologies;
- adoption of hydrogen peroxide for chemical pulp bleaching at some mills; and
- increased hydrogen peroxide and oxygen in caustic extraction stages in bleaching process.

8.4.2 Kraft Mill Requirements for Lime

Chemical kraft pulp mills need calcium oxide to regenerate the active ingredients of their pulping chemicals. Black liquor, results from chemical treatment in digesters for separation of wood fibres. This liquid containing carbon from the wood, sodium and sulphur values, is evaporated then burned with energy recovery. The chemical residue is dissolved in water (called green liquor). Green liquor contains sodium carbonate. The sodium is from the pulp treatment (digesters) while the carbon in the carbonate originates from the wood. Lime is added to this green liquor to convert the sodium carbonate to sodium hydroxide which is required for use in the pulp digesters along with sulphur. The active cooking ingredient is sodium sulphide (Na_2S). Converting the carbon to sodium hydroxide is referred to as causticizing. By making sodium hydroxide with lime (CaO), calcium carbonate ($CaCO_3$) is produced. Heating the carbonate in a lime kiln drives off the carbon dioxide and regenerates lime which can be used in causticizing.

8.4.3 CO_2 Reductions at Pulp and Paper Mills

Lime is practically fundamental to the Canadian chemical kraft pulping industry such that it is viewed as a necessity by mill operators. In the short term, technologies to reduce carbon dioxide generated from lime therefore need to focus on improvements to the overall operations of the mill (amount of chemicals used per tonne of pulp) and incremental efficiencies to the lime kiln.

Many process improvements are continually undertaken at kraft pulp mills in Canada to increase the efficiency of the process and reduce its requirements for lime and chemicals per unit of pulp produced. However, within the last 10 years there has been a focus on changes to the pulp bleaching process, in large part due to environment pressures. Mills have reduced their consumption of elemental chlorine and adopted a variety of alternative delignification and bleaching agents, such as oxygen, chlorine dioxide, and hydrogen peroxide. These changes have had an incremental impact on the amount of lime required per unit of production. Technologies, which may be applied in the future, are not likely to have a major impact with respect to reducing CO_2 from lime kilns. Given the basic requirement for sodium sulphide-based cooking of the wood fibres prior to bleaching, and the stochiometric requirements for lime in regenerating pulping chemicals economically, the demand for lime will continue. (Note: There are many changes occurring to reduce energy-related emissions from the mills).

Minor reductions in lime production and associated carbon dioxide emissions can be achieved by improving the efficiency in the use of pulping chemicals (amount applied per unit of pulp), as well as minimizing the loss of such chemicals in the production process. Some of the following technologies and practices have been applied at mills:

- higher efficiency pulp washing to recover a greater amount of pulping chemicals (sodium/sulphur values);
- oxygen injection in the lime kiln to increase efficiency; and
- improved process control.

The kraft mills continue to innovate and technologically evolve. Canadian mills may increasingly adopt such technologies as: ozone delignification; greater use of oxygen delignification; closed-loop mills; peroxide bleaching; or even ethanol based pulping. Although the effect of these technologies may improve the environmental performance of mills, their focus is not to address carbon dioxide from the lime kilns. Carbon dioxide emissions from lime kilns are not likely to be a driver for technological change within the industry.

Technologies that can impact carbon dioxide emissions from the lime kiln fall into the following categories for the purposes of description in this analysis:

- mill process changes that provide other advantages but may impact lime production and carbon dioxide emissions;
- paper market changes that can affect demand for kraft pulp;
- capture and control of carbon dioxide from lime kilns; and
- incremental changes to the lime kiln to improve efficiency.

A description of various technologies - some that are already applied by mills, others that are more likely to have a future impact - is provided. The relationship of these technologies vis-à-vis carbon dioxide emissions from the lime kiln or for the mill as a whole require focused and detailed analysis, often on a mill by mill basis. Since most of these technologies are not aimed at GHG reduction their impacts on the mills have yet to be fully assessed.

Some technologies have been developed and adopted by the mills to alleviate production constraints and/or environmental concerns. Technologies such as oxygen, enzyme and ozone delignification have typically been implemented as a means of reducing the requirements for chlorinated bleaching chemicals which have presented environmental concerns. Since the pulping side (wood fibre cooking in the digesters and associated cooking chemicals preparation) has not had the same environmental pressures, those operations have typically maximized such that the pulp is delignified to the extent possible without damaging the fibres. The brighter the pulp entering the bleachery, lower amounts of expensive brightening chemicals need to be applied. There has not been the same focus of reducing pulping chemicals (and associated carbon dioxide and other pollutant emissions). Therefore some of the technologies described below may be viewed as having potential to reduce the requirement for traditional pulping chemicals, lime use and related emissions.

8.4.3.1 Ethanol Based Pulping

The ALCELL® process is an ethanol based solvent pulping process that does not rely on sodium sulphide (or sodium hydroxide) cooking of the fibres. Ethanol acts as the active pulping agent. Repap Enterprises operated a demonstration plant in Newcastle, NB. There are no commercial pulping facilities using this system at present. Some of the key features of the technology include[103]:

- elimination of malodorous sulphurous compounds;
- elimination of recovery furnace;
- use of recovered lignins for furfural, lignosulphonates, or acetic acid production; and
- elimination of caustic/sulphur chemical recovery process including elimination of the lime kiln.

Although this technology is not commercially applied, proponents believe it may play a greater role within the industry in the future.

8.4.3.2 Modified Continuous Cooking- MCC

Modified Continuous Cooking (MCC) can take the form of Extended Modified Continuous Cooking (EMCC). "Extended" refers to extending the cooking zone in the digester. This is accomplished by adding a portion of the white liquor (cooking chemical) in different levels in the digester. Whereas in conventional cooking 100% of the white liquor is added with the pulp at the top of the digester, in EMCC cooking, as much as 30% of the white liquor may be added closer the middle or bottom of the digester. Adding the white liquor in this manner enhances the mixing process.[104]

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[103] Zhang, X., et al, "Basic Engineering Design Data for Ozone/Solvent Bleaching for ALCELL®- Derived Pulp", Pulp and Paper Canada, January 1998

[104] CHEMinfo Services Inc., "A Technical and Socio-Economic Comparison of Options to Products Derived from the Chlor-alkali Industry", For Environment Canada, 1997.

These extended delignification systems can, by themselves, decrease the lignin content of the brownstock by up to 70% compared to traditional cooking, but normally achieve a range of 25% to 40% lignin reduction. Conventional continuous cooking can render a softwood pulp to 20 kappa (a measure level of lignin reduction). However, if ozone and/or oxygen stages follow, the strength of the pulp can be severely compromised if the kappa is reduced to this level. When ozone and oxygen stages are installed, the preference is to limit the pulp exiting the digesters to higher kappa (i.e., 24 to 30) to maintain pulp strength.

Continuous digesters can be retrofitted for extended delignification. The ease and cost of modifications may vary (and in some cases may not be feasible) depending on the age, capacity utilization and other factors specific to each continuous digester. Most older models of batch digesters are not retrofitted for extended delignification. However, there are new designs of batch digesters (i.e., RDH, Superbatch®) which can be modified to yield pulp with low kappa, comparable to the output from a continuous digester with extended modified cooking.

One industry supplier promotes "low-solids" EMCC systems. This innovation incorporates multiple white liquor injection points in the digester as well as increased extraction of "dirty" chemical from the digester. Increased extraction removes "solids" around the fibres and allows fresh white liquor to better contact the fibres for delignification to occur.

Whereas in conventional continuous digesters the temperature in the cooking zone is in the range of 310°F, this can be lowered as much as 295°F using "low-solids" EMCC. Slightly higher temperatures may be required by EMCC processes alone. Operating at low temperature minimized pulp degradation, while achieving lower kappa numbers (an reducing energy costs).

8.4.3.3 Oxygen Delignification

Oxygen delignification refers to an additional stage between the pulp digesters, and the bleachery. In oxygen delignification the unbleached pulp from the digesters is washed and de-watered to high (25-35%) or medium consistency (8-15%) pulp. The de-watered pulp in then introduced into an retention tower where oxygen (1-3% of pulp volume) is introduced to the de-watered pulp under alkaline conditions (0.5-2% caustic).

The application of oxygen to the pulp prior to bleaching reduces the lignin content by 40-50%, thus lowering total bleaching agents required by about the same amount. Combined with extended cooking, oxygen delignification can reduce the lignin content to between 50-70%. The 50% reduction in lignin content from oxygen delignification is the maximum possible level which can be achieved without impairing pulp strength. There are over ten mils in Canada currently operating with oxygen delignification stages.

8.4.3.4 Ozone Delignification

Ozone is an aggressive oxidizing agent that can be used to delignify pulp. While theoretically total chlorine free (TCF) chemical pulp can be produced without ozone, most of the currently operating

TCF chemical pulp mills use ozone. The main problem in producing TCF pulp without ozone is that of insufficient brightness of the pulp. Without ozone the industry standard chemical pulp requirements of 88-90+ ISO cannot be readily achieved through extended cooking, oxygen delignification and hydrogen peroxide bleaching, alone.

Similarly to oxygen delignification, ozone delignification refers to an additional stage between the digesters, and the bleachery. In this case a retention tower applies ozone to the pulp as a 6-15% mixture in oxygen, where the ozone dosage ranges from 0.2 to 0.6% of the total weight of pulp. Ozone treatment can be combined with extended cooking and oxygen delignification to reduce the lignin content of the pulp by 70 to 80%. A major problem with ozone delignification is fibre degradation, where pulp viscosity (a measure of fibre length and strength) can be reduced by as much as 10%. No mills in Canada operate with ozone.

8.4.3.5 Enzymes

An additional means of maximizing the rate and extent of delignification in the pulping process is the incorporation of enzymes. Enzymes (e.g., xylanase enzymes) are applied to the brownstock prior to the bleaching process. Typically, the active enzyme is added to the pulp immediately after the digesters. Residence time for the enzymatic reaction to occur typically requires between 60 minutes to two hours. Some mills report that enzymes provide minor improvement in pulp brightness. The xylanase enzyme, has the function of modifying the hemicellulose content of the brownstock so that the chlorine (or chlorine dioxide) applied in the bleachery is more effective in further separating the lignin from the wood fibre. This leads to more efficient extraction of lignin in the extraction stage. However, problems with enzymes include pH control, and the temperature sensitivity of the enzymes. Enzymes are not used by most Canadian mills on a continuing basis.

8.4.3.6 Closed -Cycle Bleached Kraft Mills

Close-cycle mills operate to eliminate water discharges. Bleach plant effluents containing wood fibres, pollutants, chemicals and water are collected and recycled back through the mill. Some of the chemicals can be reused (e.g., sodium values captured for pulping) and fibres can be used as fuel. However, various constituents of the effluent cannot be recycled and need to be disposed of as solids in landfills. Closed-cycle mills may increase emissions of CO_2 and NO_x.[105]

8.4.3.7 Upgrading Mechanical Pulp

Production of mechanical pulps does not require lime calcination with associated CO_2 emissions. The technology of making improved paper grades from mechanical is rapidly progressing as a result of several driving factors. One is greater demands from customers for higher quality and a greater variety of mechanical papers. At the same time technical developments in mechanical

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[105] Simonsen, H.I., et al, "R&D Opportunities for Improvements in energy Efficiency to the Year 2010 - An Overview", Pulp and Paper Canada 96:6, June 1995

pulp and papermaking allow producers to offer improved products.[106] A few of the grades can substitute for lower quality kraft papers, where brightness and strength are of lesser importance. More R&D is required to further improve the quality of mechanical pulps and extend their grade range and market applicability. Some general areas which are the attention of, and requiring more, R&D include[107]:

- reducing yellowing tendency of mechanical papers;
- improve brightness at lower costs; and
- improve mechanical paper strengths.

There are a host of specific R&D projects involving each of these areas.

8.4.3.8 Carbon Dioxide Use at the Kraft Pulp Mills

Carbon dioxide produced in lime kilns (or elsewhere within the mill) can be used at kraft mill sites. Several uses have been identified at mills, although many other uses may exist:

- use to make precipitated calcium carbonate (PCC) on-site;
- brownstock washing;
- waste water neutralization; and
- neutralization of alkaline streams.

Kraft mills making alkaline papers often use precipitated calcium carbonate (PCC) as a filler. In many of these cases, filler is made on-site. PCC is made using purchased lime (CaO), slaking it with water to form calcium hydroxide, and passing carbon dioxide through the solution. The carbon dioxide (as a weak carbonic acid) reacts with the base - hydroxide - to form the precipitated calcium carbonate. Precise process control yields PCC with physical properties valuable to the paper making process.

As much as 30 to 60% of the carbon dioxide (containing nitrogen) gas stream from the lime kiln (excluding energy derived) can be routed to a PCC plant. How much is required by the PCC plant depends on the amount of production. At one mill where this is practiced, approximately 100 tonnes per day of carbon dioxide from the lime kiln are used for this purpose.

This application of carbon dioxide serves to minimize emissions, but does not provide a control of CO_2 releases. The reason is that lime purchased by the PCC facility, and made by a merchant lime producer, had associated CO_2 emissions. However, use of the CO_2 from the lime kiln reduces the need for purchased carbon dioxide.

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[106] Santkuyl, R.J., "SC (Supercalendered) Grades Without the Supercalender", Pulp and Paper Canada 96:1, (1995)

[107] Rodden, G., "Many Opportunities Exist for Mechanical Pulps", Pulp and Paper Canada, 96:8 , Aug 1995

One gas supplier is promoting brownstock (wood pulp before bleaching) washing using CO_2. Praxair claims that this can increase production rates for bleached kraft pulp by as much as 15% through more efficient recovery systems, while reducing effluent discharge loading and lower bleaching chemical requirements. The CO_2 is injected in the wash water of the final stage of the washing cycle. The CO_2 dissolves and forms carbonic acid which reduces pH levels. Lowering the pH reduces the fibre swelling which promotes pulp drainage and washing efficiency. Lowering pH levels in the pulp also reduces sodium losses. The CO_2 converts calcium soaps to sodium soaps thereby reducing the surface tension of the pulp slurry, which can lead to reduced needs for defoaming agents.[108]

Carbon dioxide dissolved in water produces a weak carbonic acid that can be used as similar to other acids. Carbonic acid tends to work best at higher pH ranges (e.g., 9 to 12), while greater quantities of the acid are required to achieve effects in the lower pH range. Carbonic acid may therefore displace other acids such as hydrochloric, sulphuric and phosphoric, especially when addressing neutralization at the higher pH range.

8.4.3.9 Paper Recycling and Deinking

Recycled paper is a major wood fiber source that has yet to be exploited to the full. However, the use of waste paper for a wide range of industry products has been growing steadily as advances in deinking technology, availability of more collected paper and pressure from public bodies and regulatory agencies have prompted the industry to install washing and flotation equipment to process externally-sourced waste papers for incorporation in recycled paper products.

Canadian Deinked Pulp Capacity

	1995
	(Mt/day)
Quebec	2.6
Ontario	2.2
British Columbia & Prairies	0.4
Atlantic provinces	0.1
Total Canada	5.3

Source: CHEMinfo Services Inc.

The selection of furnish for deinking operations is made in consideration of projected availability for the mill as well as the paper market to be served. Much of the Canadian capacity for recycled

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[108] Praxair, "Brownstock Washing With CO_2", Advertisement insert, Page 25. Personal conversation Praxair representatives.

paper has been focused on serving newsprint, tissue and other lower quality paper markets. Relatively little recycled fibres represent substitutes for kraft papers.

North American Markets for Deinked Pulp

(includes Canada and U.S.)

Paper market	% of total
Newsprint	55%
Tissue products	30%
Fine papers	10%
Other applications	5%
Total	100%

Source: CHEMinfo Services[109]

There are many sources of used papers, including magazines, newspapers, and office wastes. Producers of recycled deinked newsprint are utilizing old magazines (OMG) and old newsprint (ONP). OMG containing kraft pulp are incorporated to provide a strength component for the final paper. Bleached kraft grades used for magazine stock also provide a degree of brightness to the mix. Furthermore, some argue that the fillers (e.g., calcium carbonate) in the pulp result in improved flotation efficiencies, somehow contributing a scavenging action on ink particles. Nevertheless, OMG will generally make up anywhere from 5 to 35% of the paper furnish for most newsprint deinking facilities in North America. For production of tissue and fine paper, kraft based ledger waste papers are desirable.

8.4.4 R&D Capabilities in Pulp and Paper

The majority of the world's pulp and paper research and development activities has been centred in the Scandinavian countries (Sweden, Norway, Finland), Canada, and the United States. Other countries with pulp and paper industries are also involved such as Germany, Russia, other European nations, South America and even Far East nations. R&D in the pulp and paper industry is conducted by practically all members in the business system, including:

- forestry groups;
- specialized pulp and paper R&D centres;
- pulp and paper companies (mill operators);
- universities;
- equipment suppliers;
- engineering service suppliers;

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[109] CHEMinfo Services Inc., "North American Bleaching Chemicals: Outlook to 2000", Toronto, ON, 1993

- consultants; and
- chemical (including gas) suppliers.

Canada has strong R&D capabilities in the pulp and paper sector. A host of pulp and paper mills, universities and specialized centres support the Canadian industry and provide expertise around the world. In some areas, Canada's researchers have been leaders in technology development, while some of the Canadian mills have been at the forefront of technology implementation.

Environmental concerns have been a major driver for technology change in the industry over the last decade. There has been significant concern associated with discharges of chlorinated substances, including dioxins and furans, from kraft mills. This has spurred the kraft mill industry in North America to replace elemental chlorine with chlorine dioxide. In addition, some mills have adopted oxygen delignification which further reduces chemical requirements for bleaching and related discharges of chlorinated substances. A few kraft mills in North America (out of approximately 150) have, or are in the process of installing, ozone delignification technology. This technology reduces chemical loading in the bleaching process and further reduces discharges of chlorinated substances.

Mechanical pulp mills have not been faced with the same environmental pressures. The amount of R&D effort related to supporting necessary process improvements has been less than for kraft mills. Environmental pressures on mechanical mills are less since they have less potential for environmental releases. Mechanical pulping does not rely on chlorine or chlorine dioxide to brighten pulp. In addition, pulping is carried out by mechanical rather than chemical means. Although the mechanical pulping process is energy intensive (i.e., electricity) it has not received the attention given to the kraft mills. Sodium hydrosulfite, caustic and hydrogen peroxide are the main bleaching chemicals used on mechanical pulp. These chemicals have not been associated with major environmental problems. Research in this field has been more focused on maximizing quality of pulp and paper produced, and optimizing operations and expensive bleaching chemical use.

8.4.4.1 Pulp and Paper Research Institute of Canada (Paprican)

The Pulp and Paper Research Institute of Canada (Paprican) based in Quebec is one of the world leading institutions in pulp and paper research. The organization conducts research in nearly all areas of the industry, with research centres in Montreal and Vancouver.

In an industry review of about 85 technologies[110], 10 were selected for detailed analysis. These technologies have cross-cutting implications for carbon dioxide emissions reduction at lime

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[110] Simonsen, H.I., et al, "R&D Opportunities for Improvements in Energy Efficiency to the Year 2010 - An Overview", Pulp and Paper Canada 96:6, June 1995

kilns, other processes generating CO_2, and across other environmental issues. The list of 10 technologies, ranked by environmental attractiveness (not on a GHG basis) was as follows:

1. secondary treatment mill effluents - biological treatments;
2. closed-cycle bleached kraft mill;
3. oxygen and ozone bleaching;
4. deinking sludge incineration;
5. suspension firing;
6. biomass dewatering;
7. fluidized bed combustion;
8. deinking for newsprint;
9. medium consistency processing; and
10. high intensity refining (mechanical pulping control).

In the field of mechanical pulping, Paprican has conducted research on mechanisms of refining and grinding, and the property of fibres. It has a pilot plant designed to conduct experiments related to fibre quality, energy intensity and other aspects of mechanical pulps. The Finish Pulp and Paper Research Institute (KCL) has conducted major projects aimed at developing both TMP and pressure groundwood (PWG) grades. The Institute's approach to the research covers technical issues and quality throughout all parts of the value-adding production chain including: a laboratory; a mechanical pulping pilot plant; a paper machine; pigment coaters; and even a heatset offset printing press. Objectives of the research have been to develop top quality magazine papers with new TMP technology and improved PWG fibres for coated grades. PWG grades (produced with lower energy consumption) offer good printability but lower strength than TMP fibres.[111]

8.4.4.2 Industry Suppliers

Many of the larger suppliers of equipment, services (e.g., engineering) and chemicals undertake pulp and paper R&D to support their business activities. Below are examples of industry suppliers conducting R&D related to mechanical pulp and paper.

Sunds Defribrator's C$ 8 million expansion of its research facility in Sundsvall, Sweden features: a new chemical pulping laboratory; enlarged pilot plant; a new workshop; and other supporting facilities. The facilities will enable research on all core technologies for chemical and mechanical pulping, recycled fibre, and panelboard. Process research will cover screening, washing, and bleaching, including hydrogen peroxide bleaching.

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[111] Barnet, A. J., 19th Annual Leaks Survey: Refiner Capacity Now Stands at 95,470 tonnes a Day, Pulp and Paper Canada 95:3 (1994), Page 12.

National Silicates, based in the United States, with operations in Mississauga, ON is a major supplier of sodium silicate to bleached mechanical pulp mills. Sodium silicate is used in conjunction with hydrogen peroxide in mechanical pulp bleaching. The company supports their silicate business with a pilot plant in Mississauga.

8.5 Emissions from Merchant Lime Producers

In 1995, total merchant Canadian lime production was about 2.7 million tonnes, representing about 2% of the world supply and 10% of total North American production (including Mexico). There were 17 lime companies operating 20 plants ranging in size from about 50 kT to 450 kT. (This excludes lime plants situated in pulp and paper mills, and other captive production of lime. Internal pulp and paper production for 1995 is very roughly estimated at 3,400 kilotonnes, yielding approximately 2,600 kilotonnes of carbon dioxide. The average capacity of lime kilns at Canadian pulp and paper mills is approximately 100 kilotonnes per year.)

Merchant Lime Producers

(excludes kraft pulp & paper plants producing for internal consumption)

Company	Plants	Capacity (kT)	Locations
Beachvilime	2	710	Ont(2)
Greybec	2	582	Que(2)
Continental Lime*	4	515	MN(2),AB,BC
Steetley Industries	1	345	Ont
General Chemicals*	1	292	Ont
Algoma Steel *	1	275	Ont
Global Stone	1	225	Ont
Koch Minerals	1	200	Ont
Havelock Processing	1	175	N.B.
Texada Lime	1	170	BC
Other producers	5	311	
Total	20	3,800	

* Captive uses as well as merchant supply

Although, there are technologies available to remove carbon dioxide from lime kiln gas streams, rarely are these technologies applied, since the gas does not contain commercially useful products. As a result, the operating experience in handling dilute carbon dioxide streams is not well defined. While general CO_2 reduction options are available, which technology best fits the particular requirements of each facility has yet to be determined. Generally, lime producers contacted in this study had not analyzed the expensive option of controlling and ultimately needing to dispose carbon dioxide, currently emitted. Additional research is required to identify optimal solutions for the lime kilns in controlling their emissions and finding a sink for the output.

Carbon monoxide (CO), nitrogen (N_2), carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrous oxide (N_2O) are all produced in lime kilns. Carbon dioxide content can range from 10 to 40% by volume. Depending on the reduction technology, addressing CO_2 and N_2O emissions can reduce SO_2 emissions Sulphur dioxide emissions are influenced by several factors, including the sulphur content of the fuel, the sulphur content and mineralogical form (pyrite or gypsum) of the stone feed, the quality of lime being produced, and the type of kiln. The dominant source of sulphur emissions is the kiln's fuel, and the vast majority of the fuel sulphur is not emitted because of reactions with calcium oxides in the kiln. Reducing the lime content may increase sulphur dioxide emissions. Sulphur dioxide and N_2O emissions may be reduced if the pollution equipment uses a wet process.

Kiln gas streams also contain carbon dioxide resulting from combustion of hydrocarbon energy sources (e.g., oil, gas, coal, coke or biomass), nitrogen, oxygen, minor amounts of other gases and a substantial amount of particulate, largely composed of fine calcium carbonate particles. Before gas streams can be processed through carbon dioxide capture and treatment equipment, particulates in the gas stream need to be removed.

8.5.1 Cryogenics

Cryogenic separation of gases relies on distillation. Distillation requires gases be condensed to liquids. Oxygen, nitrogen and carbon dioxide which are gases at room temperatures and atmospheric pressures are liquids at low temperatures and high pressures. Cryogenic systems must therefore liquefy these gases before separation. Cryogenic technology which has been mostly applied to separation of oxygen, nitrogen and other gases in air, until about 20 years ago was the only commercially viable process for making these industrial gases. A short description of a typical cryogenic system separating oxygen and nitrogen from air is provided to identify some of the issues with respect to technology and its applicability to address carbon dioxide containing streams. The economics of these systems do not favour their application to streams containing a minor amount of carbon dioxide.

Particulate matter, water and other contaminants in the stream need to be removed before processing the stream. Particulates can be addressed with such devices as water scrubbers, electrostatic precipitators or fabric filters (baghouses). Water scrubbers also address a portion of the soluble sulphur and nitrogen oxides.

Typically, cryogenic systems require removal of water and other ingredients which can freeze and affect downstream equipment. Most of the water can be condensed out of the stream by cooling to approximately 5°C. Dehydrated air may then be fed to a molecular sieve dryer to remove trace amounts of moisture[112].

Carbon dioxide becomes a liquid below -18°C at approximately 320 psig pressure. Nitrogen and oxygen have a lower dew points and remain gaseous under these conditions. If nitrogen is the other major gas contained in the stream (as is the case with many lime kiln gases), passing the nitrogen/carbon dioxide stream through a separation column can separate the two gases. The purity of the resulting gas streams from cryogenic systems is typically very high, exceeding 99%.

Cryogenic units are capital intensive in comparison to other gas separation technologies, so they are typically not installed on-site as control equipment. However, if the volume of gas to be treated is large (i.e., 1000 tonnes per day) cryogenic facilities may be the most economical.

8.5.2 Pressure Swing Adsorption (and Vacuum PSA)

In pressure swing adsorption (PSA) units molecular sieves (carbon or zeolite based) with pore dimensions similar to the gases being separated are placed in vessels. The separation process takes advantage of one gas having an adsorption rate on the molecular sieve faster than the other. As the clean, dry gas stream (containing mixed gases) is passed through the molecular sieves under pressure, the concentration of the faster-adsorbing gas at the outlet of the vessel is lower, since is it left behind adsorbed on the molecular sieve. The outlet gas contains high purity gas that is slower to adsorb on the molecular sieve. When the vessel containing the gas left behind in the molecular sieve (faster adsorbing gas) is vented (pressure released) the gas is de-adsorbed and flows to the outlet at high concentration. Two vessels can be used to optimize the production process. While adsorption is occurring in one vessel, desorption can take place in the other. Within minutes the roles of the vessels are switched. Vacuum Pressure Swing Adsorption (VPSA) units operate similarly to PSA units but at lower pressure to reduce operating power costs.

Capital costs for PSA units can be influenced by many factors including: the concentration of the inlet and outlet gases; quantity of gas stream to be handled; and physical characteristics of gases to be treated, to mention a few. PSA units have been widely adopted for separation of oxygen and nitrogen (i.e., separation of air) at many industrial facilities, including pulp and paper mills, steel plants, and other industrial users of high purity oxygen and/or nitrogen. PSA units can produce oxygen with or nitrogen with greater than 99.5%, or higher.

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[112] Michael, K.P., "Industrial Gas: Surveying Onsite Supply Options", Chemical Engineering, McGraw Hill, Volume 104 (1), January 1997.

Capital costs curves (over a range of sizes) for PSA units separating of oxygen and nitrogen contained in air are well defined since there have been many installations and the operating parameters are similar from one unit to the other. Differences in capital cost result mainly to the size of the units relating to amount of air to be separated. Capital costs for carbon dioxide PSA separation systems are not well defined since these systems have not been designed to address carbon dioxide contained in various concentrations in a variety of gases (although most likely to be contained with nitrogen).

Capital costs for PSA or VPSA units handling 100 tonnes/day of oxygen are in the range of $1 million. Benefits of economies of scale apply to larger units, such that the cost for a system making 300 tonnes/day of oxygen will not be three times the cost of a unit making 100 tonnes/day. The feasible range of PSA units is typically 5 to 150 tonnes/day of equivalent oxygen, and 10 to 500 tonnes per day for VSPA units. If greater rates 500 tonnes per day of production are desired cryogenic units are likely to be more feasible. However, cryogenic plants are not feasible at lower rates of production.

Variable costs for separation of gases will relate, in part, to the ratio of the original concentration in the gas stream to the final concentration desired. For oxygen producing PSA systems , the variable cost is approximately C$20 per tonne[113]. Most of the cost relates to compression power costs to achieve operating pressures. For carbon dioxide PSA units, costs will depend on the concentration of the carbon dioxide and other gases in the stream being treated.

VPSA units have been applied to separating carbon dioxide. One example, identified in this study is installed at DuPont Canada's steam methane reforming unit at Maitland, ON. That unit is part of a larger process that separates carbon dioxide from methane, nitrogen and hydrogen. The VPSA unit increases the concentration of a gas stream from approximately 50% to over 98% carbon dioxide. The total system also features a catalytic oxidation of the methane which generates additional carbon dioxide (and water). Carbon dioxide and nitrogen are eventually separated by pressurizing (320 psig) and cooling the stream to approximately -20°C to liquefy the carbon dioxide, while the nitrogen remains in the gaseous phase.

8.5.3 Membrane Systems

Hollow polymeric fibre membranes can be designed to selectively allow passage of one molecule while restricting others. Gas separation is achieved by designing systems that take into consideration differences in membrane solubility and diffusion of molecules to be separated. For example, membranes are available that allow water and oxygen to permeate faster than nitrogen.

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[113] Industry supplier of PSA units

Membrane technology for carbon dioxide separations requires additional research and development. Typically these systems have not focused on removal of carbon dioxide. Commercial applications have involved nitrogen, oxygen or specialized gases.

For low purity gases (e.g., 5 to 20% carbon dioxide in a mix of streams) membranes may offer lower overall costs in achieving separation. There are many parameters which can affect the efficiency of separation. Some of the more important include:

- permeability of membrane (generally, the more permeable, the less selective);
- differential pressure through the membrane;
- temperature (permeability increases with increasing temperature);
- surface area of the membrane (surface area increases with decreasing fibre size); and
- membrane thickness.

Generally, membrane systems yield gas purities that are lower than cryogenic separation and comparable with PSA. For separations starting with concentration of the desired gas, membrane systems can be economically preferred to PSA or VPSA units. However, advances are occurring rapidly in membrane technology, such that capital costs are being lowered and the ability to separate gases is being increased.

Membrane separation systems may be suitable to address dilute carbon dioxide streams (10 to 20% by volume) from lime kilns. However, an important consideration would be the requirement to clean the stream of particulate matter or other contaminants than could affect the permeability of the membrane. Industrial grade (50 to 75% carbon dioxide) could be produced with membrane technology. Achieving greater concentrations of carbon dioxide increases the capital cost since greater amounts of membrane surface area would be required. Typically, membrane systems can achieve 95% purity for some gases.

8.6 Sequestering and Disposition of Carbon Dioxide

Once the carbon dioxide has been captured and extracted the question arises, "what can be done with it?" Existing commercial uses for carbon dioxide for beverages, refrigeration, neutralization and other applications are well serviced by gas suppliers. Typically these firms have not needed to extract carbon dioxide from dilute sources (such as lime kilns), since the cost of extraction are high relative to sources which offer a high concentration carbon dioxide stream. Gas suppliers have sought opportunistic sources of carbon dioxide from ammonia plants, hydrogen plants (e.g., at crude oil refineries), and chemical plants. Carbon dioxide producers are now charging gas suppliers for high concentration streams. Carbon dioxide can range from 1 to 30 $/tonne, although most is likely to be in the 5 to 10 $/tonne range.

Costs Structure and Market Value for Carbon Dioxide

Cost component	$/tonne-$CO_2$
Purchase price of carbon dioxide (depends strongly on purity and quantity)	0 to 30
Power costs for purification	10 to 40
Transportation, capital and profit	20 to 50
Delivered market price	100

Source: Industry CO_2 supplier

The following analysis provides a brief description of a sequestering option (as an example) and possible acid markets for carbon dioxide. Carbon dioxide is already used in these areas, but more development effort would be required to have carbon dioxide increase its market position.

8.6.1 Sequestering CO_2 in Carbonates

Carbon dioxide can be reacted with salt solutions and various alkali hydroxides to form carbonates. There are industrial facilities conducting such reactions. A well known process is the ammonia-soda process of Solvay process[114] used to make sodium carbonate (soda ash). General Chemicals of Mississauga, ON operates such a process in Amherstburg, Ontario. The process uses the carbon dioxide produced from a lime kiln as a reactant with sodium chloride to make calcium chloride and sodium carbonate. The overall reaction is as follows:

$$CaCO_3 + 2NaCl \longrightarrow CaCl_2 + Na_2CO_3$$

Whether this process results in a “permanent” sequestration of the carbon dioxide depends on the application of the soda ash. A large portion of the soda ash produced in this process is used in glass manufacture. In this case, carbon dioxide contained in the carbonate is dissociated and released during heating in the glass making process. However, in other applications, such as detergents, water treatment and some chemicals manufacturing, the carbonate may remain sequestered.

There are many other carbonates, although production may not be commercially viable. Other carbonates that can be readily made through inorganic chemical processing include carbonates of potassium, barium and magnesium. These products have limited market outlets.

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[114] Faith, W.L., et al, “Industrial Chemicals” John Wiley & Sons, Toronto, 1975

8.6.2 Acid Markets

Carbon dioxide can be dissolved in water to produce weak carbonic acid. This acid has many possible neutralization applications in a variety of end-use markets. Potential markets for carbon dioxide would include a portion of the existing hydrochloric, nitric, sulphuric and phosphoric acid markets. However, the portion of acid market in which carbon dioxide would fit would be low, since in many applications, the type of acid being used is specific to the equipment and chemistry of the process. In addition, carbonic acid works best at high pH levels, and large quantities are required to achieve results in the lower pH range.

A detailed examination of the acid markets is required before the potential for carbonic acid can be assessed. This requires a close investigation of the functional requirements for each of the sulphuric, phosphoric and other acids, along with a technical and economic assessment of carbonic acid. A few of the possible carbon acid applications are discussed below to identify some of the issues and opportunities with increased market penetration.

8.6.2.1 Water treatment

Acids are used in water treatment to provide pH control, and in the case of hydrochloric serve as a source of chlorine. Many of the industrial water circuits use hydrochloric acid both because of its ease of use, it often is already being used to some extent in other production applications. Firms with ion exchange resin systems to purify process water or to purify product require an acid to regenerate the resins, and either hydrochloric acid or sulphuric acid is used for this application. Carbon dioxide as carbonic acid may have a position in some of the neutralization markets.

8.6.2.2 Mining

The mining industry uses acids in the collection and refining of metal ores. Acids are used in the extraction of some ores, the separation and purification steps in ore processing. The water treatment area is another application in mining. The acid often is used to adjust the pH of circuits and as well as being used in the collection of gold values in the cyanide process. In the potash industry the acid is used for pH control on froth floatation circuits. Acids are also used in the processing of uranium ores. Carbonic acid already has a minor position in the mining sector and there may be potential for greater use.

8.6.2.3 Magnesium metal production

The production of magnesium consumes hydrochloric acid for the chloride process. In this process hydrochloric acid is used to produce magnesium chloride, which is then electrolytically refined to the metal. The chlorine is given off the electrolytic cells and is collected for recycling. In recycling the chlorine is burned with hydrogen to produce hydrochloric acid for use in the primary chlorination reaction. Carbon acid would not be suitable for this application.

8.6.2.4 *Oil & Gas use of HCl*

Hydrochloric acid is used directly in well completion and as an additive in a range of oil well drilling chemicals. Approximately 8 kilotonnes of HCl is used in the oil and gas fields of Alberta, Saskatchewan, BC and Manitoba both for drilling wells as well as a production aid. Most of the use of hydrochloric acid is on oil wells, rather than gas wells. Industry suppliers estimate that only 3-4% of gas wells ever require acidization, while oil wells may require some reworking every 2-3 years once they are in production. The volume of hydrochloric acid used in the oil and gas sector in Canada is estimated at 8 kilotonnes. The bulk of acid is used in stimulation and descaling of oil wells. More research and development would be required to better determine the potential for use of carbonic acid in the oil and gas sector.

8.6.2.5 *Miscellaneous applications*

Cleaning of industrial equipment, construction market cleaning applications, dairy maintenance and cleaning, industrial etching, and many minor industrial applications use some acids. The tanning industry and the production of organic pigments are other application areas using some hydrochloric acid. Very small applications (much less than 1 kilotonne) also includes the pharmaceutical and food sectors, where acids are to produce organic salts as well as a processing aid. Carbonic acid would need to be assessed on a segment by segment basis.

8.7 Emissions From Portland Cement Manufacturing

Portand cement is a mixture of inorganic chemicals - mostly, calcium oxide (lime), silica, alumina (Al_2O_3), iron and calcium sulphate (gypsum). Portland cement is made by combining clinker with a small amount of gypsum which is used to control setting time. Clinker is made by combining lime with silica containing materials. Most grades of Portland cement contain 60 to 67% lime by weight. Emission estimates are based on an average lime content in Portland cement of 63.5%[115]. The amount of energy-related carbon dioxide emissions can range from 40 to 60% of the total emissions from cement plants[116]. About 1.135 units of $CaCO_3$ are required to produce 1 unit of cement, and the amount of CO_2 released in the calcining process is about 500 kilograms per tonne of Portland cement produced.

The production of lime and clinker is an energy intensive process resulting in carbon dioxide emissions. This analysis is concerned only with emissions resulting from the evolution of carbon dioxide from the limestone calcination process, not the energy related emissions. However, some

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[115] Jaques, A., et al, "Trends in Canada's Greenhouse Emissions, 1990 to 1995", Environment Canada, April 1997.

[116] Oak Ridge National Laboratory, et al, "Scenarios of U.S. Carbon Reductions, Potential Impacts of Energy Technologies by 2010 and Beyond", Prepared for the Office of Energy Efficiency and Renewable Energy", U.S. Department of Energy, Sept. 1997.

technologies that reduce carbon dioxide emissions associated with lime production also yield GHG emission reductions associated with energy consumption for cement production.

Particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and CO_2 are the primary emissions in the manufacture of Portland cement. Small quantities of volatile organic compounds (VOC), ammonia (NH_3), chlorine, and hydrogen chloride (HCl), also may be emitted. A large portion of these emissions are from combustion of fuel sources.

8.7.1 Reduction Technologies From Cement Lime Kilns

Several technologies can reduce process emissions from cement lime kilns. The option of capturing, treating and storing CO_2 has been described above. This section described reducing the CaO content of Portland cement; and sequestering CO_2 in production of concrete products.

Much of the improvement in carbon dioxide emissions from cement plants has come about as a result of the trend toward energy-efficient "dry-production" process. Although most of the industry now uses the dry process, some cement facilities have yet to convert to that technology.

8.7.1.1 Use of Fly Ash in Cement

Fly ash, metal slags, and volcanic ash are being incorporated in cement formulations in Canada and other countries. These materials are typically waste products generated from industrial processes producing electrical energy (e.g., coal power plants) or making metals. There are products can be incorporated in cement formulations without materially affecting the performance for various end-uses.

Fly ash is a mixture of inorganic chemicals produced from the combustion of powdered coal or other fuel containing inorganic matter. In Canada, fly ash is being used in minor amounts in cement, although it is being used in a greater amount by concrete products producers. While cement formulations can use up to 8% by weight fly ash, nearly all Portland cement sold contains less than 2%. In other countries, fly ash is typically incorporated in greater amounts. The fly ash is incorporated into the mixture at the cement plant through various process operations.

Most European countries have allowed use of slags or fly ash in cements, even though the ingredient produces cements with different properties. There are reports that slags or fly ash containing cements last longer and are more tolerant of salt water than pure clinker cements[117]. However, increasing the slag or fly ash content to very high levels will compromise the performance of the cement.

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[117] Oak Ridge National Laboratory, et al, "Scenarios of U.S. Carbon Reductions, Potential Impacts of Energy Technologies by 2010 and Beyond", Prepared for the Office of Energy Efficiency and Renewable Energy", U.S. Department of Energy, Sept. 1997.

Cement Fly Ash Content in Other Countries

Region	Allowable Fly Ash Content Levels
Hong Kong	45%
Some Latin America countries	35%
Europe	20%
United States (other sources indicate no allowable limit)	10%
Canada	8%

Source: Industrial cement supplier. Allowable levels not confirmed

A recent study[118] concluded that substituting fly ash for clinker can reduce GHG emissions by 5 to 20%. This rate of reduction not only takes into account the lower levels of process CO_2 emissions resulting from less lime use, but energy-related savings resulting from processing (e.g., grinding) a lesser quantity of clinker. Other benefits of this technology option are that reductions in NO_x, SO_2 and other pollutants associated with cement production are also realized.

8.7.1.2 Costs For Substituting Fly Ash for Clinker

Fly ash or slags may be available at low cost, free of charge, or credits may even be available to cement makers to incorporate this waste material in their product. Some producers of fly ash may have financial interest in shipping fly ash waste to cement plants, rather than disposal at landfill sites at higher costs. Cement producers have interest in adopting fly ash, since they view the material as a means to lower material costs. International cement technology suppliers, active in Canada and contacted for this study express a willingness to develop new specifications for cement containing fly ash. They point to their business operations in other countries where fly ash has already been adopted.

Before fly ash could be incorporated in greater amounts in cement, cement product specifications and standards may need to be changed. This process may represent the largest cost component to this option. Changing cement product standards (or any standards) is usually not easily achieved. Time, resources and the cooperation of many stakeholders involved in the cement business as well as standard setting bodies are typically required. Changes to cement content standards take time. Related standards cement/sand mixtures dictated in building codes may also need to be modified. Changing cement specifications in Canada may also need to take into account the country's uses of cement and its unique climate conditions.

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[118] Sauer, G., "Cement, Concrete and Greenhouse Gas", Paper presented at the CGLI Second Roundtable on North American Energy Policy, April 1997

It should be kept in mind that slags, fly ash and other materials are already incorporated into concrete formulations, although the amount of such materials is not well defined. Concrete mixes are largely composed of aggregate materials and minor portions of cement that acts as the binder. The concrete manufacturing industry is composed of many participants. According to cement producers, this industry group is not interested in having cement manufacturers incorporate slags, fly ash and other similar materials in cement, preferring to do it themselves at less cost.

8.7.1.3 Sequestering CO_2 in Concrete

There are reports of technologies being developed that utilize CO_2 to produce Portland cements[119][120]. Carbon dioxide can be permanently sequestered in the cement products. The amount of CO_2 that can be sequestered can be as high as 82% of that produced in the calcining process used to make lime (CaO) at cement plants (although any other source of CO_2 can be used). These cement products boast advantages (e.g., fast setting) but there are problems to be addressed requiring technology advancement. There are also industry infrastructure barriers (e.g., transporting the CO_2), technical standards and many other issues to be considered that relate to the potential market and GHG emission reductions that can be achieved with this technology.

8.7.1.4 Research and Development

Materials research, new products development, standards development, and market development efforts will be needed to increase the amount of fly ash in cement formulations in Canada. Canadian cement producers and technology suppliers point out that customer perceptions regarding the quality of cement containing fly ash will need to change. There is a negative perception that the quality of cement containing fly ash is generally poor and not acceptable.

In Canada, research on cement and concrete products is largely carried out by universities and government laboratories. Lafarge Canada Inc. with a cement and concrete products research centre in Montreal is one of the few cement companies with R&D facilities in Canada. The University of Sherbrooke and other universities across Canada are involved with projects related to high performance concrete. Part of this research has been funded by the Networks of Centres of Excellence Program coordinated by the Federal government. The National Research Council and the Canadian Centre for Mineral and Energy Technology (CANMET) are involved with applied R&D. There are also numerous laboratories in Canada that are involved in product testing to address regional market requirements. The Canadian Standards Association (CSA), Ortech, Golder and many other engineering and material testing firms, which are also involved in a variety of other fields, support the cement and concrete producers in Canada.

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[119] Environmental Building News, Volume 4, No. 5, September/October 1995

[120] Davidovits, J., The Geopolymer Institute, News Release, July 1, 1997.

Cement Producers in Canada

(some producers have more than one plant)

Company	Location	
North Star Cement Ltd.	Corner Brook	NF
Blue Circle Canada Inc.	Toronto	ON
St. Lawrence Cement Inc.	Mont Royal	QC
Lafarge Canada Inc.	Montreal	QC
Ciment Quebec Inc.	St-Basile	QC
Tilbury Cement Ltd..	Delta	BC
ESSROC Italcementi Group	Mississauga	ON
Federal White Cement Ltd.	Woodstock	ON
Inland Cement Ltd.	Edmonton	AB
Canadian Medusa Cement Ltd.	Owen Sound	ON
Holnam West Materials Ltd.	New Westminster	BC

Some of the cement producers in Canada rely on foreign-owned parents, or national research and product development centres in the United States or elsewhere. The Canadian Portland Cement Association (CPSA) recommends the Cement Technologies Laboratory (CTL) in Skokie, IL. CTL is a for-profit laboratory and subsidiary of the Portland Cement Association (US). The organization has a staff of 150 and conducts R&D in the following areas:

- evaluation of structural failures;
- material science;
- development of new testing procedures; and
- new product development.

9. Petrochemicals

9.1 Summary

The scope of the petrochemical industry covered in this analysis includes two general areas, namely:

- use of natural gas liquids (NGLs) and crude oil based liquid feedstocks for the production of ethylene and co-products (i.e., propylene, butadiene, etc.) in large scale facilities; and
- use of natural gas - methane - for the production of ammonia, urea and methanol products.

These two areas account for the majority of GHG emissions associated with "non-energy" uses of natural gas and natural gas liquids from the petrochemical sector. Carbon dioxide emissions from these areas are summarized as follows:

Carbon Dioxide Emissions From Petrochemicals

Natural Gas Liquids and Crude Oil Based Feedstock	**1995**
Source of Emissions	(kilotonnes)
CO_2 from combustion of internally produced methane	1,500
Decoking of furnace tubes	60
Feedstock cracking	10
Total	**1,570**
Natural Gas - Methane - Based Petrochemicals	
Potential CO_2 emissions from non-energy natural gas - methane - uses	9,115
Less internal CO_2 uses already in-place	
Urea production	(2,525)
Methanol production	(3,445)
Total	**3,145**
Total estimated emissions of carbon dioxide from petrochemicals	**4,715**

Technologies to reduce GHG emissions from the petrochemical sector analyzed in this report include the following:

Petrochemicals based on natural gas liquids and crude oil based feedstocks
- alternative feedstocks;
- anticoking additives;

Petrochemicals based on natural gas - methane - feedstock
- increased production of urea using ammonia and carbon dioxide;
- increased production methanol using available hydrogen and carbon dioxide;
- improvements in energy and yields.

Hundreds of operational and equipment enhancements at petrochemical facilities can improve energy efficiency and increase yield. However, the technology options considered in the analysis deal with non-energy related emissions. These are more difficult to reduce, since some are inherently involved with the stochiometry of the chemical reactions used to make the products. Some of the many technologies not analyzed in this study but are applicable in achieving GHG reductions by petrochemical producers include:

- furnace metallurgy enhancements;
- carbon dioxide extraction with amines or other agents;
- optimize yield of products to feedstocks;
- improved process control; and
- reduced product losses.

In general these and other technologies and programs are applied by producers as part of continuing efforts to enhance long term competitiveness, increase current production capability, and operate efficiently on a daily basis. Application of these technologies and programs can achieve marginal reductions in GHG emissions relative to production volumes.

9.1.1 Costs to Reduce

Technologies for which costs have been estimated can achieve 50% to 60%, (or 2,700 kT/year) reductions in total carbon dioxide emissions. The cost of applying these technologies range $0 to $140 per tonne-$CO_2$. Switching to ethane feedstock for the portion of ethylene petrochemical production in Canada that is reliant on crude oil based feedstocks (naphtha, gas oils, etc.) may even offer economic benefits to eastern Canadian producers over time. Using ammonia to sequester carbon dioxide for urea production involves higher capital cost to construct new capacity, and has associated costs of about $29 per tonne (based on application of several simplifying assumptions).

9.1.2 R&D Requirements

Achieving reductions in emissions from the petrochemicals area approaching the targets set out in Kyoto presents strong challenges for Canada's petrochemical industry since the sector is growing rapidly in Canada. Some of the technology options identified in the study require additional research and development, and more detailed analysis on various dimensions. Emissions from the petrochemical industry will need to envision energy as well as non-energy sources of carbon dioxide, since these are inextricably linked at individual facilities and within plant complexes. Specific research and development efforts with respect to technology options identified in this analysis, include but are not limited to:

- develop improved understanding with the view to optimize petrochemical feedstock utilization under environmental and economic constraints;
- develop improved understanding of the carbon (and carbon dioxide) balance in petrochemicals, including energy-related carbon sources;
- identify available hydrogen sources for matching with carbon dioxide for methanol;
- assess the global warming potential (GWP) of ammonia fertilizers versus urea; and
- support efficiency improvements with respect to energy and yield.

Research and development efforts with respect to reducing emissions will require the participation, cooperation and guidance from petrochemical industry stakeholders in Canada. A broader and more detailed scope of analysis than that included here is required to better assess all possible options for reducing emissions while meeting other environmental and economic constraints.

9.2 Background

Petrochemicals are organic chemicals largely derived from petroleum or natural gas. Crude oil refineries and natural gas processing plants provide the raw material (feedstocks) which range from simple methane to hydrocarbons containing higher molecular weight materials such as ethane, propane, butane gas oils and naphtha. Methane is used for the production of ammonia and methanol. Natural gas liquids (NGLs), such as ethane, propane and butane, are "cracked" at high temperatures to yield petrochemical building blocks. Gas oils, naphthas and other feedstocks from crude oil refining operations are also cracked to make ethylene in conjunction with many valuable co-products. Ethylene is the primary petrochemical product made in the largest quantity. Cracking crude oil based feedstocks such as naphthas or gas oils yields higher ratios of propylene, butadiene, butylenes, benzene, toluene, xylene isomers and other co-products, in comparison to the ethylene produced. Primary petrochemicals are reacted to form chemical intermediates and polymer derivatives. These are eventually incorporated into a great variety of end-use products employed for industry, commerce and household consumers.

Canada's petrochemical plants, which currently number approximately 150[121], are concentrated in three provinces. This total includes primary petrochemicals production as well as many

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[121] Statistics Canada, CCPA

smaller secondary facilities involved in polymers and derivative intermediates production. Ontario is home to approximately half of the total. Most Ontario establishments are located near Sarnia where there are both petroleum refineries and pipeline terminals for natural gas and its liquid by-products (NGLs). Alberta has a burgeoning petrochemical industry based almost exclusively on natural gas. Two separate petrochemical complexes -- one near Edmonton, the other in the Joffre and Red Dear vicinity -- account for the bulk of the output, which was valued at $3.3 billion[122] in 1994. Quebec has plants in the Montreal area as well as downriver at Becancour. Their primary raw materials are mainly derived from crude oil based feedstocks. A methanol plant situated at Kitimat, BC is the largest facility not operating within the aforementioned provinces.

Canada is home to a mix of domestically owned, U.S. and European based multinationals. Novacor Chemicals Ltd. is the country's largest petrochemical firm headquartered in Canada. Celanese Canada is an affiliate of Hoechst based in Germany, while Dow Chemical Canada and Union Carbide Canada are wholly owned by their respective U.S. parents. Imperial Oil has minority shareholders in Canada and Exxon has majority control. Shell Canada recently transferred its chemical operations to Shell International Chemicals of London, England.

Major Canadian Petrochemical Firms

Name	**Country of Majority Ownership**	**Location of Major Plants**
Alberta Envirofuels Inc.	United States, Finland	Fort Saskatchewan, AB
AT Plastics Inc.	Canada	Fort Saskatchewan, AB
Dow Chemical Canada Inc..	United States	Fort Saskatchewan, AB Sarnia, ON
Du Pont Canada Inc.	United States	Maitland, ON Kingston, ON
Imperial Oil Ltd.	United States	Sarnia, ON
Methanex Inc.	Canada	Kitimat, BC
Novacor Chemicals Ltd.	Canada	Sarnia, ON Joffre, AB
Pétromont Inc.	Canada	Varennes, PQ
Shell Chemicals Canada Ltd.	United Kingdom	Scotford, AB
Union Carbide Chemicals and Plastics Canada Ltd.	United States	Prentiss, AB

More recently Canada has attracted companies working under joint venture arrangements to ensure market outlets for petrochemicals made domestically. Far East companies have been

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[122] Statistics Canada, CCPA

particularly active in Alberta. For example, Alberta and Orient Glycol is a joint venture between Union Carbide (50%), Japan based Mitsui (25%) and Taiwan based Far Eastern Textile Co. (25%). Shell Chemicals Canada recently announced its joint venture with Mitsubishi Chemical, based in Japan, to build a new ethylene glycol plant in Alberta. That facility is scheduled to begin operations in the year 2000. In Quebec, Pétromont and Petresa Canada are partnerships between the province's La Société Générale de Financement (SGF) and foreign corporations based in the U.S. and Spain, respectively.

The scope of the petrochemical industry covered in this analysis includes two general areas, namely:

- use of NGLs and crude oil based liquid feedstocks for the production of ethylene and co-products (i.e., propylene, butadiene, etc.) in large scale facilities; and
- use of methane for the production of methanol, ammonia and derivative products (e.g., urea).

These two areas account for the majority of potential non-energy GHG emissions from the petrochemical sector.

9.3 NGL and Crude Oil Based Petrochemicals

In Canada, ethylene is produced at four different locations and utilized at nearby plants to make intermediate derivatives which can be feasibly transported globally. The industry's major derivative end-products are polymers such as polyethylene, polypropylene, polyvinyl chloride and styrenic resins. Synthetic rubber and other polymers used in the manufacture of synthetic fibres, paints and coatings, printing inks and adhesives are also outputs from Canada's petrochemical sector. Ethylene is also used to make ethylene oxide (most of which is converted to ethylene glycol), ethylene dichloride and a variety of other intermediate chemicals.

Primary NGL and Crude Oil Based Petrochemical Producers

Company	Location	Major Products
Novacor Chemicals	Joffre, AB	Ethylene, polyethylene
Novacor Chemicals	Corunna, ON	Ethylene, polyethylene, propylene, styrene
Imperial Oil Ltd.	Sarnia, ON	Ethylene, polyethylene
Petromont Inc.	Varennes, QC	Ethylene, polyethylene
Dow Chemical Canada	Fort Saskatchewan, AB	Ethylene, polyethylene, ethylene oxide, glycol, vinyl chloride monomer, dichloroethane

9.3.1 Emissions and Trends

Intermediate products and finished goods contain much of the carbon in the original raw materials used for ethylene and co-products production. However, some of the carbon in the original feedstock is converted to methane which is captured, separated from the other chemicals and utilized as a furnace fuel in the production process. Although the methane is typically recycled, it can be transferred or sold as a fuel in petrochemical-refinery complexes. A small portion of the carbon is converted to carbon dioxide and coke (mostly carbon) which deposits on the inside of the furnace tubes.

Petrochemical Feedstock Product Yields#

	Ethane	Naphtha	Propane	Major Uses
Ethylene	76.0%	26.0%	37.7%	Polyethylene, polystyrene, PVC, glycol
Methane (oxidized to CO_2)	8.0%	10.7%	26.4%	Fuel
Hydrogen, other fuels*	7.0%	1.0%	2.8%	Fuel, Methanol
Propylene	1.6%	13.7%	11.5%	Polypropylene, Isopropyl alcohol
Propane	0.8%	0.8%	5.3%	Fuel
Butadiene	1.8%	4.6%	2.4%	Polymers
Butylenes, butanes	0.9%	8.4%	1.5%	Polymers
Heavier co-products	3.5%	33.0%	11.4%	Polystyrene, solvents, gasoline
Losses	0.4%	1.8%	1.0%	
Total	100.0%	100.0%	100.0%	

Ethylene yields are expressed with recycling ethane to extinction as is practiced by all petrochemical producers).
* Includes carbon dioxide yield - typically less than 0.02 wt%.

Major greenhouse gas emissions from the production of primary petrochemicals include the following sources:

- internally produced methane and related carbon dioxide emissions from combustion;
- carbon dioxide formed during furnace tube carbon removal (decoking) operations; and
- carbon dioxide formed from cracking reactions.

Other sources of carbon dioxide emissions associated with the petrochemical industry which are not covered in the scope of this analysis. These include carbon dioxide and a minor amount of nitrous oxide emissions related to fuel utilization (in addition to that generated from internally produced methane) and carbon dioxide separated from natural gas streams in the production of ethane feedstock.

9.3.1.1 Trends in Emissions

Canada's petrochemicals industry is in the midst of a rapid expansion. Annual shipments, which totaled nearly $10.7[123] billion in 1995, will rise as a result of capital investments underway. This spending may approach a rate of $1 billion per year until the turn of the century. In 1986 the value of petrochemical shipments was $5.4 billion. The upswing in manufacturing activity relates to better access to global markets. Exports, only $1.7 billion ten years ago, reached $6 billion in 1995. The apparent domestic demand for petrochemicals is approaching $10 billion per annum with imports accounting for approximately half the total. The United States has traditionally been Canada's most important trading partner. This relationship was enhanced by the signing of the Canada-U.S. Free Trade Agreement (FTA) and the subsequent North American Free Trade Agreement (NAFTA). Over 75% of petrochemical exports are destined for the United States.

Trends in Carbon Dioxide From Petrochemical

	1990	1995	2000F
		(kT)	
CO_2 from combustion of internally produced methane	1,200	1,500	1,900
Decoking of furnace tubes	50	60	75
Feedstock cracking	8	10	13
Total	1,258	1,570	1,988

Source: CHEMinfo Services estimates

9.3.1.2 Carbon Dioxide From Internally Produced Methane

As noted above methane is generated in the thermal process of cracking feedstocks to make ethylene and co-products. Ethylene producers typically operate their plants to minimize operating costs and maximize ethylene production. Ethane feedstock provides the best ratio of ethylene produced versus carbon dioxide generated. While this applies to the carbon dioxide generated from internal methane which is captured and combusted as fuel, it also applies to energy sources of carbon dioxide. Of the commercial feedstocks available, ethane requires the least energy consumption per unit of ethylene made. Naphtha and other crude based liquid feedstocks (e.g., gas oils) are the most energy intensive for petrochemicals production.

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[123] Canadian Chemical Producers' Association: 1995 Sector Update

Ratio of Ethylene Produced to CO_2 Emissions

(CO_2 from combustion of internally produced methane only)

Petrochemical Feedstock	$C_2^=/CO_2$
Ethane	3.45
Propane	0.52
Naphtha	0.88

* Approximate ratios, will vary depending on actual plant operating conditions

There are several reasons underlying ethane's advantage related to carbon dioxide emissions per unit of ethylene production. One reason is the inherent structure of the ethane molecule (H_3C-CH_3). In making ethylene (H_2C-CH_2) only two carbon hydrogen bonds needs to be broken. In the case of propane ($H_3C-CH_2-CH_3$), two C-H bonds need to be broken in addition to a carbon-carbon bond. That requires more energy. In the case of naphtha molecules which have longer carbon changes, many more C-C bonds need to be cracked along with more C-H bonds.

Another factor favouring ethane is the low ratio of co-products yielded in the cracking process. Ethane yields a high (76 wt%- ethane recycled to extinction) yield of ethylene to feedstock. By comparison, propane yields approximately 38% ethylene, and approximately 26% methane. Liquid based feedstocks yield low amount of methane (8 to 12%), but have a lower yield of ethylene as well, ranging from 12% (e.g., gas oils) to 27% (e.g., light naphthas). The implication of the yield structure is that less energy is required to crack the feedstocks and purify (through distillation) the final products.

9.3.1.3 Reducing CO_2 From Internally Produced Methane

Approximately 80% of the ethylene made in Canada is based on cracking ethane. All ethylene produced in Alberta uses ethane. Only eastern Canadian petrochemical facilities, which rely partially on propane, butane and crude oil liquid based feedstocks such as gas oils and naphthas to make ethylene. Historically ethane, most of which has been produced in Western Canada, has not been available to eastern Canadian petrochemical facilities. However, increasingly ethylene producers in Ontario (Imperial Oil Ltd. in Sarnia and Novacor Chemicals in Corunna) have been able to access ethane from various sources and have increased the use of this feedstock over time. However, a pipeline to deliver western ethane has not reached Quebec. Therefore, Petromont's plant in Varennes, QC continues to rely mostly on propane, butane and crude oil based feedstocks. (A small amount of ethane may be available from internal cracking production, or nearby refineries). Overall, in 1995 approximately 20% of the Canadian production of ethylene was from non-ethane feedstocks.

Feedstocks Used to Make Ethylene and Co-products

Feedstock	Portion of Total Ethylene
Ethane	80%
Naphtha, gas oils	15%
Propane, butane	5%

Switching to ethane from propane and crude oil based gas oils and naphthas can result in a 30 to 40% reduction, or approximately 500 kT in carbon dioxide emissions (associated with combustion of internally generated methane, only) from ethylene petrochemical plants. Additional reductions in energy related emissions that are not quantified in this study would also be realized.

Although a switch to ethane feedstock seems attractive from a carbon dioxide emissions perspective there are technical, economic and government issues which have influenced the availability and use of ethane at eastern Canadian facilities.

One technical factor is the ability of the operational units to accommodate ethane and the unique ratio of co-products produced. Facilities are typically designed to handle a narrow range of feedstocks. Therefore expensive modifications may be required to major equipment such as furnaces, distillation columns and compressors. Petromont and Novacor which 15 years ago relied almost exclusively on crude oil based feedstocks have made many modifications to their operations to accommodate more propane, ethane and butane. Novacor claims to have practically full feedstock flexibility, although it continues to use crude oil based feedstocks for a large portion of its production. Petromont's operations in Varennes, QC have increased the portion of NGLs. However, use of ethane would likely require major plant modifications.

Petrochemical producers operate their plants to maximize margins (not minimize carbon dioxide emissions) and satisfy contractual commitments for products. Although ethane is typically a low cost feedstock, it does not necessarily provide the optimal feedstock at all times given the structure of the eastern Canadian petrochemical industry. For example, Novacor has commitments to supply propylene, butadiene and butylenes to nearby customers making such products as polypropylene, isopropyl alcohol, rubber and styrene. Similarly, Petromont has a requirement to supply propylene to Montell's polypropylene plant in Varennes, QC. In general, given these business relationships, cracking only ethane would yield enough ethylene but not enough propylene, butadiene or butylenes to supply eastern Canadian derivative plants.

Eastern Canadian producers have increased the amount of ethane purchased over time. Imperial Oil has access to ethane from special contracts with U.S. based gas suppliers, while Nova uses ethane from Alberta delivered via the Cochin pipeline. There is no existing pipeline to deliver ethane from western Canada to Petromont in Varennes, QC. In the past Alberta has discouraged ethane exports to the United States or other provinces, encouraging the installation of ethylene plants in the province.

9.3.2 Costs to Reduce Emissions

The costs to reduce carbon dioxide emissions by switching to ethane from propane and crude oil based feedstocks (naphtha and gas oils) can vary substantially for several key reasons. A major factor is the variability of the feedstock prices and the value of co-products (i.e., propylene, butadiene, etc.). Increasing co-product values lowers the net raw material costs of propane, butane, naphtha and gas oils versus ethane. When co-product values decline, North American producers begin to favour ethane. The petrochemical industry is such that equilibrium (when the costs feedstock - expressed as $/unit of ethylene - are all equal) is seldom achieved.

Over the six year period between 1990 to 1996, the estimated average quarterly variable cost (which includes net raw material costs plus energy) of ethane was slightly lower ($20 to 30 per tonne of ethylene) than that of propane and naphtha in eastern Canada. Translating this cost into $ per tonne of carbon dioxide reduced results (using ethane for the portion of ethylene produced from propane and crude oil based liquids in Canada) in an average operating cost benefit of approximately 20 $/tonne of CO_2.

Petrochemical Feedstock Variable Costs

(net raw material costs plus energy)

Period average	1988-89	1990-96
	($/tonne ethylene)	
Ethane	210	275
Propane	130	300
Naphtha	80	300

Source: CHEMinfo Services Inc.

However, as previously mentioned this benefit may not always be available to producers. During the period 1988 to 1989, the average variable cost of ethane was much higher than propane and crude oil based feedstocks. This circumstance resulted from relatively low crude oil prices (in comparison to ethane) and relatively high values for propylene, butadiene and other ethylene co-products. Under these conditions there would be a high cost for switching to ethane. Although these market conditions did not last (since petrochemical producers used more crude oil based feedstocks to generate higher quantities of co-products, which brought their price down), the cost for using ethane can be as high as 100 $/tonne of carbon dioxide.

The operating cost of reducing carbon dioxide emissions in this area can range from 100 \$/t to a benefit of 20 \$/t-CO_2, or more. These costs do not take into consideration capital costs for plant modifications, or pipeline infrastructure required to deliver ethane to Quebec. These one-time costs can be on the order of \$100 to \$200 million - furnace modifications and downstream processing changes required. Since most of the propane and liquids cracking based ethylene production is largely feedstock flexible, plant modifications may be closer to the lower end of this order-of-magnitude estimate. The upper range of this estimate approaches the capital cost to construct new capacity (with a size to replace amount of ethylene produced from liquids). Amortized over 20 years capital costs can contribute \$20 to 40 per tonne of CO_2 reduced. Therefore, total costs may range from 0 to 140 \$/tonne of CO_2. For the majority of the carbon dioxide, the cost of reduction associated with switching feedstocks would be in the lower part of the range (0 to 20 \$/tonne) and would likely result in a benefit during periods of high crude oil prices. This cost analysis does not take into account petrochemical customer disruptions.

Cost Summary For Feedstock Substitution

Amount of annual CO_2 reduction	**550 kT**
Costs	(\$/T CO_2)
Direct operating costs	-20 to 100
Annualized capital costs	20 to 40
Total estimated cost	0 to 140

9.3.2.1 Other Implications

Switching to ethane feedstocks has important implications, beyond carbon dioxide emissions. These include impacts on energy and related pollutant releases, as well as economic implications for the industry required to compete on a global basis.

Making ethylene from ethane (versus propane and naphtha) requires less total energy. Significantly less fuel and steam are required when using naphtha or gas oils. However, since naphthas and gas oils yield more heavier (higher molecular weight) liquid products, less compression of gases is required. Therefore electricity demands may be lower (if gas compressors operate on electricity rather than steam).

Over the last 20 years, eastern Canadian petrochemical producers have moved toward greater use of ethane and away from liquid based feedstocks. The assumption is that this trend will likely continue and serve to enhance the competitiveness of the eastern Canadian facilities versus their competitors.

Using ethane reduces total feedstock requirements and therefore involves fewer fugitive and process emissions from petrochemical plants. Although low (between 0.2 and 2.0 wt% of feed), product losses (emissions and otherwise) associated with liquid based feedstocks are closer to 2% by weight, while losses from ethane feedstocks are less than 1% of feed quantity. Given there is much more liquid feed is required to make the necessary quantity of ethylene, total quantity of losses can be as much as 2 to 6 times higher than using liquid feeds versus ethane feedstocks.

The Canadian petrochemical industry needs to remain competitive to continue to attract investment, especially in western Canada. The buildup of plants in Alberta is largely predicated on the availability of low-cost hydrocarbons and operate with low cost strategies based on new large scale facilities. Plants in Alberta are among the world's lowest cost operations, typically rivaling plants in the Middle East and the most efficient U.S. Gulf Coast facilities.

9.3.3 Carbon Dioxide From Decoking Operations

Coke, which is essentially carbon, forms on the inside of furnace tubes as a result of the cracking reactions in the production of ethylene. Coke eventually builds-up to a level that restricts flow within the tubes and can adversely affect reaction kinetics. As coke builds up the efficiency of the reaction (with respect to energy requirement per unit of production) is reduced. Factors that influence the rate of coke build-up include temperature of the reaction, metallurgy of the furnace tubes, metal surface characteristics of furnace tubes, as well as other factors unique to furnace design and operations.

Furnace tubes at ethylene plants need to be decoked. The frequency of decoking operations can range from 20 to over 100 days depending on the type of feedstock, furnace design, use of anti-coking agents, and operational factors. The duration of the decoking operation is typically 1 to 2 days. Typically, furnaces are out of service 3 to 6% of the time. During decoking of a furnace, production continues at other furnaces. The decoking operations require energy. Steam is used to heat the furnace tubes and oxidize the carbon (coke) to carbon dioxide.

Typical Period Between Ethylene Furnace Decoking

Feedstocks Used	Type	Days
Naphtha	Liquid	22 - 25
Heavy Atmospheric Gas Oil (HAGO)	Liquid	17 - 20
Ethane	NGL	40 - 80
Propane	NGL	25 - 30
Butane	NGL	25 - 30

Nitrous oxide (N_2O), resulting from incomplete combustion of nitrogen is not formed in the decoking operations. (Neither is nitrous oxide formed in the cracking reaction since there is no nitrogen introduced in the reaction medium. Raw materials do not contain nitrogen and there is no air introduced into the reaction.)

9.3.3.1 Anticoking Additives

Chemical additives which can reduce coke build-up are proprietary blends that minimize the degradation reaction making carbon (C) from the feedstock molecules. They are incorporated in the feedstock in minute quantities, typically in part per million concentrations. One industry user identified dimethyldisulphide (DMDS) as an active ingredient in some formulations. Other active ingredients are also used. Suppliers are known to incorporate masking agents in the formulation to prevent competitors from identifying and copying the these expensive products.

Additives typically increase the operating time of the furnaces by 5% to 50%. This would have a comparable reduction in carbon dioxide emissions associated from this source. Actual results vary depending on the suppliers' specific formulations as well as the feedstock and furnace operating conditions, such as temperature, residence time and pressure.

Some of the additives suppliers are the specialty chemical arms of major oil producers and refiners. Their position in the market may have evolved from technology developed and applied to crude oil refinery operations, as well as the lubricants business in which some of these companies are also involved. Other firms are specialty chemicals suppliers (e.g., Nalco).

Identified Suppliers for Furnace Coke Minimization Additives

Company	Head-office Location
Amoco	USA
Phillips	USA
Nalco/Exxon Energy Chemicals	USA
Tetra	USA
Viinos	Russia

Anticoking additives are already used by most petrochemical producers to extend the service time of the furnaces. However, new chemical additive systems are being developed which offer marginal improvements in anticoking capability, and therefore marginal improvements in carbon dioxide emission reductions. It is estimated that the level of carbon dioxide emission reduction from this technology would amount only to 5 to 20% (of CO_2 from decoking activities). This represents less than 1% of total carbon dioxide emissions from petrochemical sources.

9.3.3.2 Technology Costs

Anticoking additives are already used by most petrochemical producers to extend the service time of the furnaces. Their costs are low in comparison to total variable costs, since they are incorporated into the feed in parts per million. Minor additive costs are more than offset by potential large economic benefits resulting from increased production capability. The incremental profit (product value less variable cost) of one day's production from the petrochemical industry is estimated at $1 to 2 million. This presents a large incentive for augmenting the service time of the operations even marginally.

9.3.4 Carbon Dioxide From Feedstock Cracking

A very small portion of the carbon contained in the raw material is converted to carbon dioxide. Carbon dioxide (and carbon monoxide) is avoided by petrochemical producers as it is an indication of the cracking reaction proceeding too far, with associated loss of yield in ethylene and other co-products. The objective of the reaction is to generate high priced hydrocarbons, not break down the feedstock into less valuable substances, such as methane or carbon dioxide.

Approximate Yields of Carbon Dioxide

(weight% of product per unit of feed)

	Naphtha	Ethane	Propane
Carbon dioxide	0.01%	0.02%	0.02%
Ethylene	26%	75%	37%

Source: Canadian producers

A very small portion of the carbon dioxide contained in the product stream is captured and controlled with amine extraction processes.

9.3.5 Other Technologies and Programs to Reduce GHG Emissions

Many other technologies can increase the efficiency of petrochemical operations and thereby reduce emissions of GHG. These include:

- furnace metallurgy enhancements;
- carbon dioxide extraction with amines or other agents;
- optimize yield of products to feedstocks;
- improved process control; and
- improved product loss control.

In general these and other technologies and programs are applied by producers as part of continuing efforts to enhance long term competitiveness, increase current production capability, and operate efficiently on a daily basis. Application of these technologies and programs contribute to marginal reductions in GHG emissions relative to products made.

Furnace metallurgy and design technology evolve, albeit slowly and at high cost. Furnace design enhancements reduce the capital cost of equipment as furnaces become larger with a capability to process more feedstocks per unit of time. Research continues to design furnaces which better control operating conditions to achieve optimal product yields. Managing temperature, pressure and residence times of the feedstock in the furnace can yield significant economic benefits, with a low level of reductions in GHG.

9.4 Methane Based Petrochemicals

Methane, the major component of natural gas, is used for production of petrochemicals. In Canada, natural gas is utilized in large scale ammonia plants. Carbon dioxide emissions can result from these operations, although some of the carbon dioxide is used as raw material for the production of urea. Methane is also used in the production of methanol which makes use of its own production of carbon dioxide. An approximate Canadian carbon dioxide balance for the "non-energy" use of natural gas[124] is provided below.

Carbon Dioxide Balance for Methane Petrochemicals

	1995
	(kilotonnes)
Potential CO_2 emissions from non-energy natural gas - methane - uses	9,115
Less internal carbon dioxide uses	
Urea production	(2,525)
Methanol production	(3,445)
Carbon dioxide emissions (energy related)	3,145

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[124] The "non-energy" methane (as reported by Statistics Canada catalogue # 57-003-XPB) and applied by Environment Canada for GHG emission estimates) includes petrochemical consumption for chemical reaction as well as energy.

Technologies to reduce "non-energy" related carbon dioxide emissions from methane based petrochemical production discussed in this report include:

- increased urea production to chemically sequester more carbon dioxide; and
- evaluate hydrogen availability to match with carbon dioxide sources for increased production of methanol.

There are many other technologies related to reducing ammonia and methanol uses in application markets. In addition, there are energy-related technologies which will reduce the emissions from these petrochemical facilities. Furthermore, carbon dioxide from ammonia plants can be captured, extracted, and stored or sequestered. This option is not analyzed here but has implications with respect to use of carbon dioxide for enhanced oil recovery in Western Canada, where most of the ammonia capacity is situated.

9.4.1 Increasing Urea Production Using Ammonia and Carbon Dioxide

Urea is made by reacting ammonia with carbon dioxide. Approximately 0.6 kg of ammonia and 0.75 kg of carbon dioxide are required for every 1 kg of urea made. Typically, urea production is integrated to ammonia plants which also produce spare carbon dioxide. Production involves the following chemical reaction.

$$2NH_3 + CO_2 \longrightarrow NH_2CONH_2 + H_2O$$

Nitrogen and hydrogen react in the presence of a catalyst at high temperature to produce ammonia. Ammonia plants typically rely on reforming methane contained in natural gas for their hydrogen needs. Steam methane reforming (SMR) plants yield hydrogen in sufficient quantities to support large scale ammonia production. Carbon dioxide is produced as a by-product. Liquid cryogenic air separation plants are typically employed to obtain the nitrogen (with oxygen as co-product).

Methane Reforming for Hydrogen Production

$$CH_4 + 2H_2O \longrightarrow CO_2 + 4H_2$$

Ammonia Synthesis Reaction

$$N_2 + 3H_2 \longrightarrow 2NH_3$$

A large portion of the carbon dioxide produced from ammonia plants is already used to make urea. Canadian production of urea accounts for about 42% of total ammonia production and 55% of the total domestic demand for ammonia. More than half of the urea produced in Canada is exported.

Canadian Ammonia Supply and Demand Pattern

	1995
	(kt)
Capacity	4,700
Production	4,655
Canadian Applications	
Urea production	1,900
Nitric acid	310
Ammonium nitrate	222
Ammonium sulfate	120
Ammonium phosphates	146
Other fertilizer uses	655
Mining, refining	21
Pulp & paper	14
Other amines, nitriles	12
Miscellaneous	15
Total domestic demand	3,415
Net Trade Exports (imports)	1,168

Source: CHEMinfo Services, Camford Information Services

The rest of the ammonia is used in fertilizer applications (i.e., ammonium nitrate, phosphate, sulfate), with a minor portion used for animal feeds, amine production, mining, pulp and paper, and miscellaneous applications. Ammonia is sold in anhydrous and aqua (granular and liquid) forms for direct application to soil as a fertilizer, as well as being used as an chemical intermediate for production of other fertilizer types. Canada has become a dominant supplier of ammonia-based fertilizers to the U.S. because of its lower production costs due to favorable natural gas supplies.

Major urea producers include the ammonia producers, namely: Agrium, Canadian Fertilizers, Saskferco and Terra. There is also vertical integration (i.e., make both raw materials and final products) among the ammonia nitrate, sulfate and phosphate producers. Agrium and Terra are examples of this integration. ICI and Cominco rely on purchases of ammonia for fertilizer production.

Canadian Ammonia and Urea Capacities, 1995

Company	Plant location	Ammonia (kT)	Urea (kT)
Canadian Fertilizers	Medicine Hat, AB	1100	500
Agrium	Redwater, AB	800	600
Agrium	Ft Saskatchewan, AB	600	390
Saskferco	Belle Plaine, SK	500	700
Agrium	Carseland, AB	450	590
Terra International	Courtright, ON	400	160
Agrium	Joffre, AB	350	0
Methanex	Kitimat, BC	300	0
Simplot Chemical	Brandon, MB	200	155
Total capacity		4700	3095

Source: CHEMinfo Services, Camford Information Services

9.4.1.1 Costs to Reduce By Making More Urea

The cost model for reducing carbon dioxide emissions by sequestering with ammonia involves construction of new urea production facilities. The amount of carbon dioxide available from natural gas - methane - petrochemicals in Canada was 3,145 kilotonnes for 1995. (This is higher in 1997 and will increase). The number of urea world-scale - 750 kT/year - plants that would need be constructed to sequester all of the carbon dioxide is about 5.5. However, there is not enough ammonia production in Canada to support this level of additional urea production. There is approximately 1,700 kilotonnes of ammonia that is either exported (1,168 kT in 1995) or applied as anhydrous ammonia (~550 kT). The simplifying assumption is that this ammonia would be available for urea production. The number of urea plants that can be constructed with this amount of ammonia is approximately 3.8 (at 750 kT/year capacity each).

The capital cost to construct a 750 kT/year urea plant in Canada is roughly estimated at C$200 to 300 million[125]. For the purposes of this analysis, the simplifying conservative assumption is that production will provide only a 0% return on investment versus selling ammonia on the market. Most urea plants achieve better returns, but with increased urea on the market, returns may turn out to be low, or even negative for some periods.

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[125] Industry sources

Capital Cost Examples For New Urea Plants and Expansions

Company	Location	Year	Capital	Quantity
			(C$ million)	(kT)
Indian Farmers Fert. Coop	Aonia, India	1996	418*	770
Nagarjuna Fertilizers & Chemicals Ltd.	Kakinada, India	1998	$349*	525

* cost to construct a urea and ammonia plant

** expansion of existing facility

Assumptions and Cost Calculations to Reduce Emission

Assumptions for Cost to Reduce Calculations		
Size of plants (capacity in kT/year of urea)	750	
Investment per plant ($ million)	$250	
Number of plants required	3.8	
Total investment ($ million)	$950	
Carbon dioxide controlled	2147	
Return on investment (over 20 years)	0.0%	
Reduction Cost Calculations	**($ million)**	**($/tonne-$CO_2$)**
Annualized capital costs (@10%, 20 years)	$112	$52
Annualized cash flow for 0.0% return on investment	($50)	($23)
Net cost to reduce	**$62**	**$29**

9.4.2 Increasing Methanol Production Using Hydrogen and Carbon Dioxide

Methanol is a commodity chemical made by reacting hydrogen with carbon dioxide or monoxide. Hydrogen and carbon oxides are produced from hydrocarbon sources, such as natural gas, oil, or even coal. Methanol plants usually obtain hydrogen by reforming methane contained in natural gas. Steam methane reforming (SMR) plants yield hydrogen in sufficient quantities to support large scale production. Carbon dioxide is a co-product of the process.

Methane Reforming for Hydrogen Production

$$CH_4 + 2H_2O \longrightarrow CO_2 + 4H_2$$

Methanol Synthesis Reactions

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$$

or

$$CO + 2H_2 \longrightarrow CH_3OH$$

Increased production of methanol which uses carbon dioxide does not necessarily translate into reduced carbon dioxide emissions. The problem is that hydrogen is required for the reaction, and the hydrogen is often derived from steam methane reforming which uses energy and generates carbon dioxide. More work is required to better define the stochiometric and energy uses (which generate carbon dioxide) for hydrogen and carbon dioxide around methanol and other petrochemical complexes. Matching available hydrogen (i.e., where hydrogen is used as a fuel) for combination with carbon dioxide sources for the production of methanol can reduce emissions.

Methanol Supply/Demand For Canada

	1995 (kT)
Nameplate capacity	2,405
Capacity utilization	104%
Production	2,504
Imports	6
Total supply	2,510
Domestic demand	725
Exports	1,785
Total disappearance	2,510

Source: Camford Information Services

Methanol consumption has experienced significant growth since the beginning of the decade, fueled mostly be the emergence of the MTBE industry. Another strong market for methanol has been the production of chlorine dioxide by pulp mills. Production of methylamines has experienced significant growth in recent years. Methanol demand for formaldehyde production has been driven by the growing building board industry where it is used to make formaldehyde that eventually incorporated in panelboards.

Methanol demand is expected to continue to grow in North America. In Canada, the installation of a new MTBE plant in Western Canada should add a major quantity of new demand. Methanol demand for formaldehyde production will be driven by the growing building board industry.

Canadian Methanol Capacity

Company	Plant location	1995
		(kT)
Methanex	Medicine Hat, AB	1,120
Methanex	Kitimat, BC	500
Celanese Canada	Edmonton, AB	780
Celanese Canada	Millhaven, ON	5
Total Capacity		2,405

Source: Camford Information Services

9.4.3 Energy Efficiency Improvements

A reminder is provided regarding energy efficiency improvements associated with ammonia and methanol plants since a portion of the "non-energy" natural gas sold into petrochemicals is in fact used for energy purposes. However, it was not in the scope of this study to cover the many technologies related to energy efficiency improvements.

The technology of making hydrogen and then ammonia has not changed appreciably over the last several decades. However, the technology has evolved to energy requirements for the process. At one time, 40 to 45 MMBTU were required to make one tonne of ammonia. That requirement has now dropped to 25 MMBTU for the most efficient plants. New ammonia plants need to adopt state-of-art technology to ensure efficient energy use and competitiveness. Similarly the energy efficiency of making methanol has also improved. Some of the older Canadian units are much less energy efficient than newer facilities. However, the amount of methane and carbon dioxide required for chemical reactions are determined by the stochiometry and product yields.

9.5 R&D Capabilities and Requirements

Achieving reductions in emissions from the petrochemicals area approaching the targets set out in Kyoto presents strong challenges for Canada's petrochemical industry which is rapidly expanding.

Some of the technology options identified in the study require additional research and development, and more detailed analysis on various dimensions. Emissions from the petrochemical industry will need to simultaneously encompass energy as well as non-energy sources of carbon dioxide, since these are inextricably linked at individual facilities and within plant complexes. Specific research and development efforts with respect to technology options identified in this analysis, include but are not limited to:

- develop improved understanding with the view to optimize petrochemical feedstock utilization under environmental and economic constraints;
- develop improved understanding of the carbon (and carbon dioxide) balance in petrochemicals, including energy-related carbon sources;
- identify available hydrogen sources for matching with carbon dioxide for methanol;
- assess the global warming potential (GWP) of ammonia fertilizers versus urea; and
- support efficiency improvements with respect to energy and yield.

This report provides a general analysis of the impact of various petrochemical feedstocks with respect to GHG emissions. This option requires more detailed analysis taking into consideration energy related emissions, other life-cycle factors, economic and even political factors.

Western Canada is now the nation's centre of gravity for the petrochemical industry, having shifted from Ontario over the last 20 years. Alberta and Saskatchewan have ethylene facilities, ammonia plants, methanol plants and other infrastructure elements (e.g., oil refineries and other petrochemical facilities) that may offer raw materials (e.g., hydrogen) as well as dispositions for carbon dioxide. Research is required to better assess the potential links between various industrial complexes in Western Canada, as well as the rest of Canada.

Although increased urea production presents an attractive option for sequestering carbon dioxide with ammonia, questions arise as to the GWP potential of urea versus ammonia. This study identified conflicting information with respect to emissions of N_2O from ammonia and urea. The emission factors used the 1995 Greenhouse Gas Inventory suggest that urea offers significantly lower emissions of N_2O versus ammonia[126]. This would support greater urea production and application. Other sources indicate that there is little difference between ammonia and urea, as far as N_2O emissions are concerned. No information was found with respect to carbon dioxide emissions from applied urea. Since urea is quite soluble in water, a portion of the carbon released from urea may be dissolved and may form carbonic acid which may ultimate form carbonates with minerals in the water. Obviously more analysis of this scenario is required.

Research and development efforts with respect to reducing emissions will require the participation, cooperation and guidance from petrochemical industry stakeholders in Canada. A broader and more

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[126] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, April 1997.

detailed scope of analysis than that included here will likely be required to better assess all possible options for reducing emissions while meeting other environmental and economic constraints.

9.5.1 Canadian R&D Capability

The fact that numerous multinationals participate in Canada's petrochemical industry is an indication that the competitive technologies are mostly being applied. Petrochemical technology suppliers parent companies operate internationally and license their know-how in order to maximize return on their research and development investments. The petrochemical business requires a long term commitment to major expenditures for research and development. R&D is not necessarily undertaken in a country in proportion to the sales generated by a manufacturing plant in that jurisdiction.

There appears to be a trend by parent firms to locate R&D activities close to their head office. Canada's chemical producers contend that this policy overlooks the fact that doing R&D in this country is very cost effective. According to a study conducted by the Canadian Chemical Producers' Association[127] several years ago, Canada has an adequate supply of qualified scientists such that companies need to spend less on administrative and support personnel than they do elsewhere. Calculated on the basis of supporting a researcher's work, a Canadian company would pay 17% less than would another facility operating a laboratory in Japan. The differential would be even higher in the United States and the United Kingdom (19%) and for Germany (42%). Also cited is the tax code in Canada which gives more favourable treatment to R&D expenditures than do the federal administrations of other G7 countries. The Canadian government allows credits for not only current operating costs but also for all capital outlays.

There is, however, a modicum of R&D already being carried out. Some of technologies developed in Canada have been licensed abroad. Several of the leading companies making chemicals in Canada are involved with university collaborations designed to undertake R&D projects not only in new processes but also in enhancing environmental performance. Some Canadian universities offer specialized expertise and research capabilities in polymer catalysis and other petrochemical processes.

9.5.1.1 Petrochemical R&D Related to GHG

Most of the organizations conducting research relating to technologies identified in this study with potential to reduce GHG emissions are located in western Canada. The petrochemical producers themselves, some universities and specialized research centres service the needs of the industry. Some organizations are involved with furnace design, coking issues and metallurgy enhancements. Additives development is mostly carried out in the United States at the R&D

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[127] CCPA: A Review of the Competitiveness of Canada's Policy and Business Environment for the Chemical Manufacturing Industry, June 1994.

facilities of the chemical suppliers. Demonstration projects or tests are often conducted in collaboration with petrochemical producers.

Operational research and process development including yield optimization and feedstock selection are part of normal operations of the petrochemical facilities. These firms continually seek to optimize feedstocks, minimize product losses and control pollution.

Identified Organizations Conducting R&D in Canada

Organizations	Location
National Centre for Upgrading Technology (NCUT)	Alberta
Westaim	Alberta
Saskatchewan Research Council (SRC)	Saskatchewan
University of Saskatchewan	Saskatchewan
University of Alberta	Alberta
CANMET	Ontario, Alberta
Novacor Chemicals	Alberta
Imperial Oil Ltd.	Ontario
Petromont Inc.	Quebec
Dow Chemical Canada	Alberta
Alberta Research Council	Alberta

Many organizations outside of Canada are involved with R&D in the petrochemical field. Major international feedstock furnace and other petrochemical equipment technology designers such as Kellogg, KTI, Stone and Webster, and Lumus all have a strong presence in Texas. The U.S. Gulf Coast region is home to a cluster of petrochemical facilities and crude oil refineries that serve as the market base for these technology suppliers.

9.5.1.2 R&D for Energy Efficiency, Yield Improvements for Methane Petrochemicals

Ammonia production technology is provided by international engineering firms and patent holders which sell their technology and services. These firms include: ICI based in the United Kingdom; M.W. Kellogg from the U.S., and Lummus based in the U.S.

Methanol production R&D is conducted by suppliers which install and support facilities around the world. These include: ICI, M.W. Kellogg, and other design and engineering firms. ICI, based in the United Kingdom has been a major provider of methanol production technology over the years. The company's low pressure technology was instrumental in converting the industry from the less efficient high pressure process. Older plants use a high pressure method (~340 atmospheres) whereas the newer plants, including those in Canada, use pressures in the 50-100 atm. range. Low pressure plants feature lower by-product yields, lower energy costs as well as lower maintenance and investment requirements.

10. Nitric Acid Production

10.1 Summary

The emissions of N_2O from nitric acid production in Canada are concentrated at one site. Eight of nine existing nitric acid plants have catalytic reduction technologies already installed which are assumed to substantially control N_2O emissions to low levels. There is potential to control N_2O emissions from the remaining existing facility, and additional N_2O emissions from a new plant that has been recently installed at the same site. Use of non-selective catalytic reduction (NSCR) technology can achieve an estimated overall reduction of 60% of total N_2O emissions with associated costs of approximately \$400 per tonne N_2O reduced, or \$1.3 per tonne CO_2 equivalent.

10.2 Background

Nitrous oxide is emitted in small amounts as a combustion by-product in the nitric acid production process. Nitric acid is manufactured from ammonia. The total domestic production of nitric acid in 1995 was 991 kt. Over 80% of nitric acid (HNO_3) is used as an intermediate in the production of ammonium nitrate (NH_4NO_3), an inorganic solid used for nitrogen fertilizer and explosives. Nitric acid is also used as an oxidant in the manufacturing of adipic acid, at DuPont's Maitland, ON plant. Less than 5% of the nitric acid produced is used for uranium extraction and the preparation of specialty explosives.

Canadian Nitric Acid Plants

Company	**Location**	**Type**	**Capacity**
Existing (1995)			(kt/yr)
Agrium Inc.	Ft. Sask, AB	high pressure	175
ICI Canada	Beloeil, PQ	dual pressure	90
	Carseland, AB	#1: dual pressure	290
Hydro-Agri	Maitland, ON	#1: high pressure	65
	Maitland, ON	#2: high pressure	85
	Maitland, ON	#3: high pressure	160
Simplot Canada	Brandon, MB	#1: high pressure	100
	Brandon, MB	#2: high pressure	65
Terra International	Courtright, ON	high pressure	120
Existing Total			**1150**
New in 1998			
ICI Canada	Carseland, AB	#2: high pressure	90
Simplot Canada	Brandon, MB	#3: high pressure	100

Source: CHEMinfo interviews; Camford Information Services

In 1995, five (5) companies operated a total of 9 nitric acid plants at 6 site locations in Canada. Two companies are expanding their facilities by each adding a new plant, each coming onstream in 1998, which will bring the total to 11 plants by the end of 1998. The total capacity for nitric acid production in Canada in 1995 is estimated at 1150 kt/yr.

Nitric acid plants are often integrated with ammonium nitrate production plants at the same site. Agrium, Simplot and Terra use the majority of their nitric acid for the production of ammonium nitrate fertilizers, which account for over 70% of ammonium nitrate demand. The remaining demand is for industrial grade ammonium nitrate, used primarily for explosives. ICI Canada is the largest domestic producer of industrial grade (explosive) ammonium nitrate. Its Carseland, AB nitric acid plant is the largest in Canada and is integrated with the largest ammonium nitrate plant in Canada. Hydro-Agri Canada sells the majority of its nitric acid, produced at Maitland, ON, to its neighbour, DuPont, for adipic acid manufacture.

10.2.1 Process

Production of nitric acid is basically a two stage process involving catalytic oxidation of ammonia to nitrogen dioxide and then subsequent formation of nitric acid by addition of water. The first stage is the reaction of ammonia gas with oxygen (from air) at high temperatures in the presence of a platinum/palladium wire-gauze catalyst.

Stage 1 (Reaction): $NH_3 + xO_2 \text{ -----> } NO + NO_2 + H_2O$ (+ trace N_2O and N_2)

The reaction products are a mixture of nitric oxide (NO), nitrogen dioxide (NO_2) and water vapour with trace amounts of nitrous oxide and nitrogen also formed. The colourless NO and brown NO_2 gases are defined as the components of NOx. An excess of oxygen drives the nitric oxide to be converted to nitrogen dioxide. The hot gases pass through many sheets of wire-gauze usually made from alloy wire knitted into a fine mesh surface. Some catalysts also use gold or rhodium in the alloy.

The second stage is the hydration of cooled nitrogen dioxide with water in an absorber tower to form a 60-65% solution of nitric acid leaving the bottom of the tower. Excess air is added at the bottom tray of the absorber tower to complete the conversion of nitric oxide (NO) to nitrogen dioxide (NO_2) within the tower, so that it can be absorbed. Water is added at the top of the tower to hydrate the nitrogen dioxide and also scrub the gases. Since the hydration reaction is exothermic, the absorber tower requires cooling. Some towers have a cooling circuit on each tower tray.

Stage 2 (Absorption):

$$2NO + O_2 \text{ -------> } 2NO_2$$

$$3NO_2 + H_2O \text{ -------> } 2HNO_3 + NO$$

The typical conversion yield to nitric acid is 93% using a fresh reaction catalyst. As the catalyst ages and degrades, conversion can fall to about 90% before changeout. The tail gases that leave the absorber tower consist mostly of nitrogen, a small concentration of oxygen, and trace quantities of nitrous oxide (N_2O), nitric oxide (NO), nitrogen dioxide (NO_2) and other nitrogen oxides.

10.2.2 Production Technologies

The two basic types of nitric acid production technologies, referred to as high pressure and dual pressure types. High pressure designs are used commonly in North America and use a single pressure throughout the reaction and absorption stages. In these designs, the tail gas concentration of NOx typically ranges from about 2,000 to 6,000 ppm. This must be controlled to outlet levels of about 150 ppm for provincial NOx objectives and catalytic reduction technology is employed. Eight of the nine existing Canadian nitric acid plants are high pressure designs, which have non-selective catalytic reduction (NSCR) abatement technology installed. The two new nitric acid plants starting up in 1998 are also high pressure designs and each has an abatement unit. The new Simplot plant will use an NSCR abatement, but the new ICI Carseland, AB plant will use an SCR abatement unit which does not address N_2O emissions.

Dual pressure designs, developed in Europe, use low pressure for the reaction stage and higher pressure for a more efficient absorption stage. The efficiency of the absorption can be increased by extending the absorber tower (increasing the number of trays) or installing a secondary tower. NOx levels are controlled to the 150 ppm range by the extended absorption. No abatement technology is therefore required on this design of plants to meet provincial NOx guidelines. The dual pressure design is used in the two existing ICI Canada nitric acid plants. ICI Canada designed their large Carseland, AB plant with an extended absorber and their small Beloeil, PQ plant with a double absorber. The Beloeil plant uses a catalytic abater on the tail gas for NOx abatement. There is no abatement unit installed on the existing Carseland plant.

The concentration of nitrous oxide in the tail gas depends on the reactor conditions and the catalyst, but typically ranges from 1000 to 2000 ppm. The N_2O concentration is usually less than half of the NOx concentration in this stream.

10.3 Emissions and Trends

The emissions of nitrous oxide from nitric acid production have been estimated at about 3 kt/yr over the last 5 years[128]. The estimates were based on the averaging of emission factors ranging from 2 to 20 kg N_20 per tonne ammonia used, as provided by European industry in 1990 and

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[128] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, April 1997.

1991. The average emission factor employed in the inventory was 8.5 kg N_2O per tonne of ammonia used, which corresponds roughly to 3 kg N_2O per tonne nitric acid produced.

Nitric acid production has remained relatively stable during this period, ranging from 910 to 991 kt, a variation of only about 9%. Therefore, nitrous oxide emissions are estimated to have been fairly steady as well. Nitric acid emissions are forecast to increase slightly as production increases to fill the new capacity.

Nitrous Oxide Emissions from Nitric Acid Production

	1990	1991	1992	1993	1994	1995	2000
N_2O Emissions (kt)		2.7	2.9	2.8	2.7	3.0	3.5
Nitric Acid Production (kt)	na	912.1	959.6	916.7	910.0	990.6	1150

Average Emission Factor Used: 3 kg N_2O/ tonne HNO_3
Source: Camford Information Services, Nitric Acid profile, Aug. 1996

10.4 Technologies to Reduce Emissions

Of the technologies listed in this section, only the first (catalytic reduction) has significant reduction potential. The others have been identified as possible techniques to reduce N_2O emissions by marginal amounts.

10.4.1 Catalytic Reduction

The control of nitrous oxide emissions is a new issue for nitric acid plants. To date, plants have installed technology to control NOx emissions only. There are two main types of catalytic reduction technologies currently used to control emissions of the NOx components (NO and NO_2) by reducing them to inert nitrogen. They are called Non-Selective Catalytic Reduction (NSCR) and Selective Catalytic Reduction (SCR). The former technology also controls nitrous oxide.

NSCR abatement uses a reducing gas (such as natural gas or hydrogen purge gas) in the presence of a reduction catalyst (often platinum on a honeycomb ceramic base). In the NSCR process, natural gas (chiefly methane, CH_4), first consumes the excess oxygen in the tail gas stream and then, once starved of free oxygen, uses the various nitrogen oxides as an oxygen source, thereby reducing them to nitrogen. Water and carbon dioxide are also present in the exhaust gases. The operating temperatures are high, usually about 1200°F. This process can only be used on tail gas streams having excess oxygen concentrations less than 2.5%, since the reactions would generate too much heat for the catalyst to remain viable at oxygen concentrations beyond this level. The high pressure design plants commonly use NSCR abatement technology. Eight of the nine existing Canadian plants already have this technology installed.

SCR abatement uses ammonia as a reducing gas in the presence of a catalyst. It operates at lower temperatures (550 - 1100°F) than the NSCR process. Like the NSCR process, the ammonia first consumes the excess oxygen and then reduces nitrogen oxides to nitrogen and water. NOx emissions, (NO and NO_2) are reduced up to 95%. No existing Canadian plant currently uses SCR abatement, but the new ICI Canada Carseland nitric acid plant (#2) has an SCR unit in the design.

Johnson Matthey, a leading catalyst supplier, has addressed the viability of these technologies for N_2O reduction. A 1991 technical update[129] provided by the company states:

> "Nitrous oxide (N_2O), commonly known as laughing gas, has been detected in significant amounts in the tailgas exiting the absorber column in nitric acid plants. Stringent emission regulations are expected in the near future. N_2O levels in tailgas are between 1000-2000 ppm. Which control technology is best?
>
> Option #1: Selective Catalytic Reduction (SCR) with Ammonia
> Fact: SCR **does not** reduce N_2O emissions. Plants using SCR technology will have to purchase additional pollution control equipment to control N_2O.
>
> Option #2: NOx Abatement with Reducing Gas (i.e. Natural Gas) - [NSCR]
> Fact: NSCR **does** reduce N_2O emissions. In fact, the conversion of N_2O will be at least as high as the conversion of NOx using NSCR.
>
> Nitric acid producers with plants using [NSCR] catalyst can rest assured that their N_2O emissions are being reduced to the same degree as their NOx emissions. Nitric acid producers planning to retrofit or install a new plant should consider N_2O emissions in addition to NOx when evaluating a pollution control system. Otherwise, the pollution control system may have to be upgraded at additional cost."

According to this technical bulletin, N_2O emissions can be reduced by up to 90% using NSCR technology. A technical manager from Engelhard, another leading catalytic reduction technology supplier, supported the claim that N_2O reduction did occur with NSCR technology, but he did not know what percentage occurred.

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[129] Johnson Matthey, "The Gauze Wire" (A Technical Update for Users of Woven Precious Metal Catalysts), Oct. 1991

There is some evidence to support the assertion that the original estimations of nitrous oxide emissions are overstated for Canadian plants. First, since 8 of 9 existing plants use NSCR abatement, which apparently reduces N_2O levels up to 90%, the average emissions for these plants are likely closer to 100-150 ppm in the tail gas, or less than about 1 kg per tonne HNO_3. Second, there is anecdotal evidence of an unidentified dual pressure double absorption plant in the US having an N_2O emission factor of about 3 kg N_2O per tonne HNO_3, much lower than the 1991 European emission factors used to calculate the 1995 GHG inventory.

If the above information on NCSR N_2O abatement is valid, it appears as though the largest single source of nitric acid N_2O emissions in Canada come from the ICI Canada nitric acid plant in Carseland, AB, which does not use any abatement. Although the control of NOx emissions has been designed into the process, it is unclear whether the extended absorption has any significant effect on reduction of N_2O emissions. ICI Canada reports that they have no actual tail gas data, but that an emission factor of 9 kg per tonne HNO_3 has been assumed for their Carseland plant. This is an upper bound estimate based on ICI's knowledge of other dual pressure design plants. Using this emission factor, the Carseland plant emissions (max 1.8 kt/yr) may represent up to about 60% of the total nitrous oxide emissions (3.0 kt/yr) calculated in the inventory.

It also appears that ICI's new nitric acid plant starting up in 1998 at Carseland with SCR abatement (which apparently doesn't reduce N_2O) may also be a significant source of N_2O emissions. Assuming an average (unabated) emission factor of 5 kg N_2O per tonne HNO_3, this new plant could possibly add another 0.5 kt/yr. With these assumptions, there may be potential to reduce N_2O emissions at one site by 90%, or about 2.1 kt/yr. This would represent up to about 70% of the total current Canadian N_2O emissions from nitric acid production. It is assumed that N_2O emissions from other sites with abatement are too insignificant to pursue. A sector-wide testing program for N_2O emissions from nitric acid plants is recommended to identify and quantify the sources.

The installation of NSCR abatement systems is roughly estimated to cost between $1 and $3 million per plant, depending on the scope of work required. Catalyst costs are about C$4000 per 1000 SCFM, or in the range of $0.2 - 0.4 million per charge for nitric acid plants. The lifespan of a catalyst averages about 5 years. Pressure vessels, piping and ducting, heat exchange equipment and installation all add significantly to the cost. The cost penalty from the increased pressure drop has not been considered. The main operating cost is the consumption of natural gas, which can range in cost from $0.2 to $0.5 million per year, depending on volume and oxygen content. This cost is offset by the energy credit obtained through energy recovery in the turbo expander for the front end of the process.

Assuming that an NSCR abatement unit designed to handle the tail gas streams from both nitric acid plants (existing and new) in Carseland, AB costs $3.0 million installed, with operating costs of $0.1 million/yr for catalyst and $0.4 million/yr for natural gas, the total annualized cost at 10%

over 20 years is roughly $0.9 million/yr. Using this scenario, the reduction cost for 2,100 tonnes of N_2O (630 kt CO_2 equivalent) is calculated at about $1.30 per tonne CO_2 equivalent.

10.4.2 Thermal Reduction

Thermal reduction technologies have been identified for NOx control. It is assumed that high temperature reduction may also be effective for N_2O control. Two types of thermal reduction technologies identified are: Non-Selective, Non-Catalytic Reduction (NSNCR) and Selective Non-Catalytic Reduction (SNCR). Like NSCR, NSNCR uses hydrocarbon gases, such as natural gas, in a low oxygen environment, but without a catalyst. The fuel reduces the nitrogen oxides. This process, known as "burnout", operates above 1500°F. The SNCR process can be used in higher oxygen environments, but uses urea to reduce nitrogen oxides. The temperatures range from 1700 - 2100 °F. This process is patented by Nalco FuelTech. The higher temperatures drive up the costs for these processes, due to increased heat exchange requirements and fuel usage.

10.4.3 Change in Catalyst Precious Metal Content

There have been some developments in catalyst technology that have been identified as having a minor effect of reducing the amount of nitrous oxide generated in the first stage ammonia oxidation reaction. Catalysts containing low palladium levels or none at all have been found to create marginally lower concentrations of N_2O by-product. The effect is called a "secondary effect" since it only deals with reductions of a few percent. For example, with a palladium-free catalyst, the emission factor for N_2O might be reduced from 3.0 to 2.9 kg per tonne HNO_3. However, this catalyst has roughly the same cost as the typical Pt/Pd/Rh catalysts and poses no known significant cost barrier.

10.4.4 Post Reaction Heat Exchange System Changes

This option is anecdotal and is only included for reference. One nitric acid manufacturer with multiple plants has noticed that the N_2O levels are lower in the plant which has lower post-reaction cooling. In this plant, the reaction gases are allowed to remain hotter for a longer period. Above 500°C, N_2O can break down into N_2 and O and this may be enhanced in the hot outlet pipes. Levels of 800 ppm are observed in this plant compared to about 1000-1200 ppm in an adjacent plant. This may be an area for investigation.

10.5 Canada's Technology Capabilities

The catalyst industry in Canada is characterized by customized production for selected end uses. The major companies are the few multinational catalyst suppliers which have set up operations in Canada to serve specific needs among oil refineries, chemical plants and other users. Canada has little activity in the development of catalytic reduction technology. Most research in this area takes place at research centres located near the foreign based head-offices of the large catalyst companies.

The development of nitrous oxide reduction catalysts is an emerging field of study. There are only a few known suppliers of catalytic reduction technology in North America. Engelhard (Iselin, NJ) and Johnston Matthey (Wayne, PA) were the only two suppliers mentioned by nitric acid industry sources interviewed. Both technology suppliers offer SCR and NSCR technologies. Other catalytic reduction systems suppliers include Huntington, Durr and Nalco.

Major Catalytic Reduction Technology Suppliers

Company	Location
Anguil Environmental Systems Inc.	Milwaukee, WI
Durr Industries	Plymouth, MI
Engelhard Corp	Iselin, NJ
Huntington Environmental Systems	Schaumberg, IL
Johnson Matthey	Wayne, PA
Nalco Fueltech	Naperville, IL

Engelhard has been active in pursuing N_2O abatement technology and they claim they have developed one of the only specific N_2O reduction catalysts on the market. Johnson Matthey was developing specific N_2O abatement technology in the early 1990's, but promising lab work did not perform to expectations in pilot scale evaluations. One source claims that Johnson Matthey is no longer participating in the zeolite honeycomb NOx SCR market.

10.6 Recommendations

The problem of N_2O emissions from nitric acid plants is limited to one major source. Suggestions for development work include:

1. Work with ICI Canada to develop strategies to reduce existing and potential N_2O emissions.

2. Support N_2O catalyst development efforts.

3. Assess broader markets of N_2O catalyst technology.

4. Work with the Canadian Fertilizer Institute (CFI) to initiate a testing program for nitric acid plants to identify, quantify and monitor the sources of N_2O.

11. Aluminum Production

11.1 Summary

Two different greenhouse gas emissions come from the anode in smelting pots in the primary aluminum production industry. In 1995, an estimated 3,600 kt/yr of CO_2 was emitted from the consumption of carbon anodes and another 5,600 kt/yr of CO_2 equivalent was emitted in the form of perfluorcarbons (PFCs) formed in anode events. These emissions come from 11 smelters which employ a range of smelting technologies. Better process control and carbon anode baking technology can reduce CO_2 emissions by a small percentage, assumed to be only 5%. Research into inert anodes which would eliminate CO_2 emissions is being conducted, but development is expected to be longer-term. Improved alumina feed process control can reduce PFC generation by 10-50%. Old smelting technologies are being replaced with new technologies under a long-term plan.

11.2 Background

The Canadian primary aluminum industry has a total production capacity of 2.3 million tonne of metal per year from a total of 11 smelters operated by 5 companies. Since electrical energy is the single most important variable cost for aluminum smelting, all Canadian smelters are located near sources of inexpensive, hydroelectric power. With the exception of Alcan's Kitimat, BC smelter, all other smelters are located in Quebec. This concentration makes Canada, and especially Quebec, the third largest producer of aluminum in the world, behind the US and The Commonwealth of Independent States (former Soviet Union).

Alcan Smelters and Chemicals, based in Montreal, operates 7 of the 11 Canadian smelters and has just under 50% of the total capacity. Alcan has several smelters which have small capacities and use older, horizontal-stud Söderberg (HSS) technology. Some of Alcan's newer smelters use production technology developed by Alcoa (US).

The four other companies operate one smelter each. Canadian Reynolds (a subsidiary of Reynolds Metals Co. Ltd. - US) purchased their smelter in Baie-Comeau several years after its startup in the late 1950's. It is now the largest smelter in Canada and one of the largest in the world. Reynolds employs 180,000 amp Pechiney electrolytic cells in most of its smelter. Some technology borrowed from Sumitomo (Japan) is also employed.

Primary Aluminum Production Capacity in Canada, 1992

Company	Location	Type	Origin Year	Capacity (kt/yr)
Alcan Smelters and Chemicals Ltd.	Kitimat, BC	VSS		272
	Isle-Maligne, Alma, QC	HSS	1950's	73
	Beauharnois, QC	HSS	1950's	48
	Grande Baie, QC	CWPB	1983	180
	Arvida, Jonquière, QC: #1	HSS	1950's	84
	Arvida, Jonquière, QC: #2	SWPB	1960's	148
	Laterrière, QC	CWPB	1987	204
	Shawinigan, QC	HSS	1901	84
Aluminerie de Bécancour	Bécancour, QC		1986	360
Canadian Reynolds Metals Co. Ltd.	Baie-Comeau, QC		1957	400
Aluminerie Lauralco Inc.	Deschambault, QC		1992	215
Aluminerie Aloulette Inc.	Sept-Iles, QC		1992	215
Total				2283

Source: Aluminum Association of Canada

Aluminerie de Bécancour is a joint venture of Reynolds (US), Alumax (US) and Pechiney (France). It also employs 180,000 amp Pechiney technology. The two other companies operate new smelters with the latest technology and 300,000 amp Pechiney cells. Aluminerie Lauralco Inc. is a subsidiary of Alumax Inc. (US). Aluminerie Aloulette Inc. is a joint venture of an international consortium involving companies from Germany, Austria, Netherlands, Japan and the Quebec Government.

Primary aluminum production in Canada in 1995 was 2172 kt, represented about 95% of capacity. Roughly 40% of this unalloyed primary production is exported. The major domestic end uses are: transportation (29%), packaging (23%) and building and construction (19%).

11.3 Emissions and Trends

There are two types of GHG emissions from aluminum smelters: CO_2 emissions from carbon anode consumption; and perfluorocarbon (PFC) emissions from anode events. Each of these emissions comes from the anode in a smelter pot, but for different reasons.

11.3.1 CO_2 from Anode Consumption

In 1995, carbon dioxide emissions from aluminum smelters were 3,600 kt, representing approximately 40% of GHG emissions from this sector. There has been a 33% increase in emissions from 1990 levels. Increases in aluminum production have driven total anode consumption while initiatives to reduce anode consumption rates have partially offset emissions. Efforts to replace older technologies with newer technologies through capital stock replacement will continue to reduce average anode consumption rates over the next 15 years. However, production increases due to economic growth with related increases in aluminum demand (particularly automobile and aerospace growth) will likely drive total CO_2 emissions higher. The estimate for the year 2000 is based on growth of primary aluminum production at 2% per year.

CO_2 and PFC Emissions from Aluminum Smelting

	Units	1990	1991	1992	1993	1994	1995	2000
CO_2 Emissions	kt	2,700	3,000	3,000	3,800	3,600	3,600	4,000
PFC Emissions	kt CO_2Eq	5,700	6,700	6,700	7,800	6,800	5,600	<5,000
Sum of GHGs	kt CO_2Eq	8,400	9,700	9,900	11,600	10,400	9,200	<9,000
CF_4 Emissions	kt	0.82	0.97	0.97	1.13	0.98	0.80	
C_2F_6 Emissions	kt	0.08	0.10	0.10	0.11	0.10	0.08	
Aluminum Production	kt	1,567	1,822	1,972	2,309	2,255	2,172	2,400

Notes: 1. Source: Trends in Canada's Greenhouse Gas Emissions 1990-1995, Environment Canada
2. CF_4 emissions trend estimated from total PFC trend using GWP of CF4=6500
3. C_2F_6 emissions trend estimated from CF_4 trend using factor of 10%.

Carbon dioxide emissions are generated by the consumption of carbon anodes in the aluminum production process. In a smelter, carbon anodes are made from finely crushed petroleum coke mixed with pitch to form a paste which is formed into a solid anode. Carbon anodes react with the oxygen generated from the alumina (Al_2O_3) to produce carbon dioxide gas and must be replaced periodically (on average, every 20 days of production).

The four smelter technologies used in Canada include (from old to new): horizontal-stud Söderberg (HSS), vertical-stud Söderberg (VSS), side work pre-bake (SWPB) and centre-work pre-bake (CWPB). The two pre-bake technologies involve pre-baking the carbon paste over several days to obtain a hard, solid anode which has lower carbon consumption rate. The HSS technology has higher carbon anode consumption (450-540 kg C per tonne aluminum) than newer pre-bake technologies (400-450 kg C per tonne aluminum).

11.3.2 Perfluorocarbons from Anode Events

Perfluorocarbon (CF_4 and C_2F_6) emissions were 0.88 kt in 1995 (a CO_2 equivalent of 5,600 kt/yr, on a GWP basis). These emissions represent roughly 60% of greenhouse gas emissions from primary aluminum production. Emissions in 1995 were relatively unchanged from 1990, despite peaking in 1993 at a CO_2 equivalent of 7,800 kt. The trend will likely continue downward as smelters continue their installation of process control systems to control alumina levels and minimize anode events.

11.4 Technologies to Reduce Emissions

The technologies to reduce greenhouse gas emissions are currently being applied as process control modifications to existing operations to improve carbon anode consumption and minimize the frequency of anode events. There is no currently available alternative which will completely eliminate CO_2 or PFC emissions.

11.4.1 CO_2 from Anode Consumption

The two technologies to reduce CO_2 consumption include research work to develop on inert anodes and replacement of old anode technology with prebake anode technology.

11.4.1.1 Inert Anodes

Theoretically, the generation of CO_2 and PFCs from carbon anode consumption could be eliminated by the use of inert anodes, also known as "dimensionally stable" anodes. This subject has been an area of primary research for every major aluminum company over the last 40 years without significant progress.

The objective of this research is to find an alternative anode material which has the following ideal properties:

- will not react with the oxygen generated from the alumina
- insoluble in the cryolite (Na_3AlF_6, a powerful flux) bath
- be extremely conductive

Alcan reports that there is a theoretical reversible operating voltage of 2.2 volts for an inert anode and only 1.2 volts for carbon anodes. This apparently imposes an energy penalty of 1 volt through the selection of the alternative process. Alusuisse discovered an energy consumption of 14.25 kWh/kg Al using SnO as compared to 13.2 kWh/kg Al for efficient processes with carbon anodes.

The most promising materials presently being evaluated are ceramic/metal composites consisting primarily of nickel oxide and nickel ferrite with a copper/nickel metal phase (Windisch and Strachan 1991). If successful, the advanced cell would result in an approximate 27% reduction in the electricity requirements for primary aluminum production.

The potential to reduce CO_2 emissions with this technology is 100% if it can be commercialized. It is not possible to develop cost estimates of this technology without a clearly defined option. Alcan is not pursuing direct research into this area at present.

11.4.1.2 Replacement with Prebake Anode Technology

Alcan has stated that it is in the midst of a long-term project to replace all HSS and SWPB technologies by higher performance centre-work prebake (CWPB) technology. The project will be complete by the year 2015. This smelter conversion project will gradually decrease the average rate of carbon consumption to more efficient levels. In 1982, the Alcan average carbon consumption was about 540 kg/t aluminum. This has been reduced to about 500 kg/t aluminum by 1995 and is projected to be reduced to the low 400 levels when current technologies are fully installed in all smelters by 2015.

The theoretical minimum rate of carbon anode consumption in aluminum production has been calculated as 350 kg carbon per tonne aluminum produced. Most smelters operate at consumption rates ranging from 410 to 420 kg/t. With best practices and technologies currently available, the industry has only been able to achieve best rates of 400 kg/t. There is a lot of potential for ongoing research to close this gap between theory and practice through better process developments.

Through these efforts, Alcan has already reduced potential CO_2 emissions by about 220 kt/yr from 1982 levels. For example, the new 200 kt/yr Laterrière plant which started up a 1989 replaced old potlines taken out of operation in the Jonqiuère complex and reduced CO_2 emissions by about 88 kt/yr, while retaining equivalent production capacity. After 1995, the conversion of the remaining old technology plants will reduce CO_2 emissions by an estimated 130 kt/yr from 1995 levels.

Alouette claims that their state-of-the-art facility in Sept-Iles uses a "300 kA technology is instrumental in achieving low energy consumption, high current efficiency (CE) and low carbon consumption."[130]

The potential to reduce emissions through prebake technology changes is limited. No more than about 10% reduction can be achieved with prebake technology. It is assumed that only 5% reduction can be achieved with low cost process control improvements and the gradual upgrading with newer technologies. The net cost of this option is difficult to estimate. A low net cost is assumed due to the low cost of process improvements. For the analysis, the costs were assumed to range from a benefit of $2/t to a cost of $2/t.

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[130] Aluminerie Aloulette, VCR Letter of Intent, Jan 29, 1996

11.4.2 Perfluorocarbons from Anode Events

PFC emissions are generated from within the smelting pots during "anode effects." Anode effects are described as the overvoltage disturbance of the smelting process that occurs when there is insufficient alumina is dissolved in the electrolytic bath and are caused by a decline in alumina levels in the smelting pot. During these events, the fluorine from the cryolite bath reacts with the carbon anode to form CF_4 and, to a much smaller extent, C_2F_6.

Perfluorocarbon emissions can only be reduced through improved control of the alumina feed to all points in the process to prevent the onset of anode events. There are two main elements of improvement in control. The first is a change in smelting technology which incorporates a redesigned feed system involving a more distributed feed point network. The second is the use of distributed process control systems to sense and adjust conditions in the electrolytic bath given existing pot technologies.

An example of the feed system improvement is given by the conversion from older Horizontal Slab Söderberg (HSS) process smelters to a point breaker feeder system. In one example of a typical HSS process cited, the crust on electrolytic bath is broken on the side every 6 hours or so and alumina is injected into the bath. The feed frequency is low and the number of feed points per pot is low. In a point breaker system, pistons break the bath crust at several locations to inject a small amount (1.0 - 1.5 kg per injection per point) of alumina at much shorter intervals. With better cell signal measurements and the use of a neural network, each distributed feed point can be controlled individually, resulting in better control of the alumina concentration throughout the bath. Theoretically, there is no technical limit to PFC reductions with increased neural networks and distributed feed control. Practically, it is assumed that a 20% reduction is easily possible with improved process control systems.

The aluminum industry has implemented many of these process improvements to reduce the number of anode effects as well as their duration. Over the last 5 years, Alcan has reduced the number of anode effects per pot per day in all their plants, to various degrees. In the newer plants having CWPB technology, the reductions have been substantial[131].

The Laterrière Works reduced the number of anode effects from 1.39 to 0.55 effects per pot per day from 1991 to 1995, which reduced PFC emissions by 60 tonnes per year (over 300 kt/yr CO_2 equivalent).

The Jonquière SWPB facility reduced the number of anode effects from 1.42 to 1.01 effects per pot per day from 1990 to 1995, which reduced PFC emissions by 90 tonnes per year (over 450 kt/yr CO_2 equivalent).

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[131] Alcan Smelters and Chemicals Ltd., Canada's Climate Change: VCR Program Report, July 1996

Alcan's four older HSS facilities reduced the average number of anode effects from 0.73 to 0.55 effects per day from 1990 to 1994, which reduced PFC emissions by 40 tonnes per year (over 200 kt/yr CO_2 equivalent).

The VSS technology used at Kitimat, BC does not allow the same degree of reduction as other pots. However, the smelter is committed to keep emissions at 1990 levels through operational control.

Aluminerie Alouette in Sept-Iles, QC built a state of the art smelter in 1992. It claims that "intensive use of computers (one per pot) gives a close control on the pot operation which translates into less anode effects, resulting in lower CO2 and PFC emissions."[132]

Part of these improvements are due to installing better computer control systems. An estimated order of magnitude cost would be about $1-2 million per facility. However, the main PFC reductions are due to many continuous process improvements that cannot be quantified. Using these assumptions of 20% reduction and $2 million per facility, the cost of reduction is calculated as about $2.3/t CO_2 equivalents reduced.

11.5 R&D Capabilities and Requirements

The Canadian aluminum industry directly employs about 16,000 people and there are 500 people involved in research and development activities among them. The Aluminum Association of Canada (Montreal, QC) is a founding member of the recently created Aluminum Research and Development Centre of Québec (CQRDA). The industry grants many research projects to organizations such as the Québec Industrial Material Research Institute (IMRI) of the National Research Council of Canada, CANMET laboratories, or École Polytechnique of the University of Montréal.

The Aluminum Association of Canada and member companies also participate in an international study dealing with perfluorocarbons (PFCs).

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[132] Aloulette VCR letter

The Aluminum Association (the US association based in Washington, DC) has recently published a number of studies that overlap into the environmental area. These include the following:

1. Aluminum Technology Roadmap Workshop
   (lists technical barriers, guidelines for people working in the aluminum technology field).
2. Partnership for the Future
   (how aluminum industry can work with government: Dept. of Energy, EPA)
3. Dimensionally Stable Anodes
   (currently in draft form; recommends a documentation of the problem)

The Aluminum Association has made a number of recommendations stated in its Technology Workshop report[133]. Selected recommendations from this report that focus on GHGs include:

Performance Targets

- Cost-effectively minimize the generation of PFCs
- Improve Bayer process productivity 20%
- Reduce/eliminate CO_2 emissions during smelting

Technology Barriers

- Lack of basic knowledge on dimensionally stable anodes
- Method to continuously measure Al_2O_3 concentration
- Material to withstand cryolitic exposure
- Need control strategy to go with new sensors

Research Needs

- Inexpensive continuous and semi-continuous sensors for measuring alumina concentration
- Feed-forward, real-time control technology
- Variety of near-, mid-, and long-term R&D activities on anode and cathode technologies
- Development of new non-carbon anodes, eliminating CO_2 emissions and improving cell performance
- Processing methods for these materials

The majority of Canadian research work is done by Alcan Smelters and Chemicals Ltd., which has a total annual research and development budget of about $100 million. The Alcan Research Centre, located in Arvida, PQ, has a budget of about $35 million and it is estimated that about a quarter of this goes toward various studies which deal with direct or indirect reductions in greenhouse gas emissions of CO_2 and PFCs[134].

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[133] Energetics Corp., Report of the Aluminum Technology Roadmap Workshop, Nov. 19-20, 1996, for Office of Industrial Technologies, US Dept. of Energy, The Aluminum Association)., Feb 1997

[134] J.P Huni, Director of R&D, Alcan Research Centre, Arvida

The initial serious work on inert anodes was conducted by Alusuisse in the 1960's and 1970's. Their work identified tin oxide (SnO) as one leading alternative anode material. SnO is one of the few oxides which will conduct at 1000°C and resist the flux of the cryolite bath.

The most intense research period was in the 1980's with work conducted by Alcan, Alcoa, Reynolds (US), Aluminum de Pechiney (France) and Comalco (Australia). Among the more promising materials being evaluated were ceramic/metal composites, called "Cer-met" composites. One such compound consisted primarily of nickel oxide and nickel ferrite with a copper/nickel metal phase (Windisch and Strachan 1991).

One of the main issues is that materials such as iron oxide (FeO, Fe_2O_3), copper oxide (CuO) and tin oxide (SnO) tend to reduce more easily than aluminum and deposit at the cathode before the aluminum deposits. This contaminates the aluminum with unwanted metals which cannot be separated. It is possible to use these metal oxides in an inert anode (degradation of 2-5 mm/yr) but the contamination of the aluminum product is unacceptable. Most primary aluminum is traded according to its purity. Premium grades contain over 99.9% aluminum and can be used anywhere. Grades having about 99.5% aluminum are restricted for use in cables due to lower electrical conductivity caused by impurities.

Some metals, such as magnesium, sodium, potassium, lithium, calcium and cerium may deposit after aluminum and can be separated later due to their reactivity.

In the 1980's, Alcan found that the use of cerium on the anode could form a self protecting cerium oxide layer that was still permeable to electric current. The oxide was found to build too high a resistance and slow down the electric current transfer.

Primary research on inert anodes is continuing today on a small scale in a few locations in the world. Currently, there is no direct research in this area by Alcan in Canada. These research initiatives are estimated to have budgets in the range of $1-2 million/yr each and include:

1. Norsk Hydro is working jointly with the University in Trondheim, Norway.
2. Comalco is working jointly with Prof. Walsh in New Zealand
3. Aluminum de Pechiney is doing some primary research in inert anodes. Most work, however, is focused on their leading-edge process technology.

11.6 Recommendations

The Environmental Technology Advancement Directorate can consider developing working relationships with the Aluminum Association of Canada and individual primary aluminum companies to assist in the development of high priority research needs to reduce greenhouse gas emissions from aluminum manufacturing. There is potential for support in various ways:

- support single company research (e.g., Alcan);
- promote industry-industry collaborations; and
- develop industry-government partnerships.

Since Alcan Smelters and Chemicals plays a significant role in the worldwide aluminum industry, there is an opportunity to align with its Canadian-based smelter research programs to support research focused on Canadian smelting operations.

One of the primary research needs is to assist the development of anode and cathode technologies, particularly the development of new materials for non-carbon anodes. Other related research needs include: designing experiments to select alternative materials; and developing potential processing methods. There is a lack of basic materials knowledge on dimensionally stable anodes, and so there is a need to support work for a systems-approach to designing these anodes. Research on inert anodes represents a long term initiative, but has a potential for significant CO_2 reductions and strong potential for technology transfer, if achieved. While basic research into this activity is no longer being carried out in Canada, this area is receiving attention from various multinational aluminum companies and universities. Developments in that field have large significance and should be closely monitored.

The other major research area for support is the development of continuous sensors, control systems and feed systems for the control of alumina concentration in smelter pots. Many companies have implemented some of these systems, but there is potential to improve the design and transfer the technology.

There is also the option of aligning with the industry-government partnership that has been formed in the US between The Aluminum Association and the US Department of Energy, Office of Industrial Technology. Together, they have developed a joint approach to identifying the industry technology barriers and managing the research needs.

12. Magnesium Production

12.1 Summary

The primary and secondary magnesium industry is the largest source of sulphur hexafluoride (SF_6) emissions in Canada, accounting for an estimated 75 tonnes of SF_6 in 1995, or about 1,900 kt/yr of CO_2 equivalent. SF_6 emissions come from its use as a component in cover gas in two magnesium smelters (Norsk Hydro and Timminco) and 5-10 magnesium diecasters. The Norsk Hydro plant is a world-scale magnesium plant and is the largest of all the sources. A doubling of capacity at this plant in the next few years will increase SF_6 emissions in the short term. SF_6 emissions have been steadily reduced by applying better process control at the smelters.

Norsk Hydro is performing research in Norway on an SO_2 cover gas system, which is planned to replace SF_6 within 10 years. The cost for a 100% reduction through SO_2 substitution is not known, but believed to on the order of $10 million in capital with cost savings through use of less expensive SO_2 gas. SO_2 is much less expensive than SF_6. The cost for a 10% reduction through better process control is estimated at about $1.9/t CO_2 equivalent reduced. A net benefit of $0.5/t CO_2 equivalent reduced was calculated based on savings in chemical costs.

12.2 Background

SF_6 is a heavy, inert specialty gas that has a 100-year global warming potential, estimated to be 23,900 times that of carbon dioxide. Small amounts of this gas have a significant impact on greenhouse gas totals. All Canadian supply is imported. The total Canadian market demand for SF_6 is estimated roughly at 200 t/yr. The gas is produced in the U.S by 2 producers, who participate in the highly specialized fluorinated compounds industry.

North American Production of SF_6

Company	Location
Air Products	Hometown, PA
AlliedSignal Specialty Chemicals	Metropolis, IL

AlliedSignal has a much larger share of the SF_6 and fluorinated compound business because it focuses on the commodity, industrial grade businesses. Air Products makes many small volume, specialty fluorinated compounds primarily for the electronics industry and has a smaller plant, estimated to be 10% of the capacity of the AlliedSignal's.

The Canadian market is supplied by specialty gas distributors who ship SF_6 in cylinders, in three different grades: (in increasing purity) commercial, instrument and very-large scale integration (VLSI). Most SF_6 sales are packaged in cylinders of 6 lb, 35 lb, 115 lb and 130 lb sizes. The major Canadian distributors are Air Products Canada Ltd., Praxair Canada Inc. (sourced from AlliedSignal) and Canadian Liquid Air.

Estimated Canadian SF_6 Supply/Demand, 1995

	1995 Volume (t/yr)
Imports	200
Electric Equipment	120
Primary Magnesium Production	50
Secondary Magnesium Processing	25
Miscellaneous (Electronic, Medical, Analytical)	5
Total	200

Source: Interview with Canadian distributor, CHEMinfo estimates

SF_6 emissions result from its use as a blanket gas for primary magnesium production and secondary processing operations. In Canada, the SF_6 used for magnesium operations is estimated to be about 35-40% of the total demand (or about 75 t/yr). Worldwide this end use represents perhaps only 10-15% of SF_6 consumption. Canada has a greater fraction because of the significant size of the domestic primary magnesium industry.

The other main end use is as an insulating gas (dielectric) for electrical utility equipment, representing roughly 80% of demand worldwide. There are numerous miscellaneous uses for high purity SF_6 in the electronics, small metal parts and medical products industries which may account for less than 5% of worldwide use. In Canada, the market split is believed to be closer to 60% for electrical equipment use. In 1995, an estimated 120 t/yr was sold for electric use and 75 tonnes was sold to the magnesium industry. The other uses of SF_6 will be discussed in another section.

12.2.1 Magnesium Production and Processing

When casting molten magnesium in primary production or secondary processing operations, an inert blanket gas is required to protect the magnesium surface from oxygen, because of the strong tendency of magnesium to oxidize explosively in air. While the inert gas is composed largely of nitrogen or carbon dioxide, SF_6 is used as a small component in the mixture to aid the protection of the magnesium surface and control burning. Concentration levels have typically been about 1% in the inert gas. SF_6 is a very heavy gas (roughly 3 times heavier than air) and settles quickly to the surface with little turbulence in a contained surface area. When SF_6 contacts molten magnesium, it chemically reacts with the magnesium to form a thin, impermeable molecular skin which is non-oxidizing. The "skin" can be separated later from the molten magnesium, leaving the latter in high purity form. This technique is preferred to the mixing of non-oxidizing fluxes with the magnesium because the purity issue is critical in diecasting operations.

SF_6 is also not harmful to humans in the range of concentrations used for magnesium production. The threshold limit value (TLV) issue is not significant. Sulphur and sulphur dioxide have been used for this purpose in the past, but use was discontinued due to health concerns and odour problems. Concentrations of SO_2 above 3 ppm are considered a workplace hazard.

In the past, the aluminum industry used to use SF_6 for degassing of molten aluminum. SF_6 scavenges oxygen (contained in air) from molten aluminum. Its use has been replaced with chlorine gas.

Primary and Secondary Magnesium Production in Canada

Company	Location
Primary Producers	
Norsk Hydro	Becancour, QC
Timminco	Haley Station, ON
Secondary Processing	**(Diecasters)**
Trimag	Haley Station, ON
Dynacast	Pointe Claire, PQ
Magnesium Products Ltd.	Strathroy, ON
ITM	Quebec City, PQ
Indalloy	Rexdale, ON

There are two primary magnesium production plants operating in Canada. The Norsk Hydro facility in Becancour, PQ is the largest and one of several this market leading company operates worldwide. It has a capacity of about 45 kt/yr, but will double in size by the year 2000, due to high demand growth for diecast automotive parts. A second, much smaller facility is operated by Timminco in Haley Station, ON. It has a capacity of about 4 kt/yr and produces magnesium, calcium and strontium alloys.

Magnesium ingots are processed into diecast alloys for auto and aerospace parts. The diecasting process also requires the use of a SF_6 blanket gas, since the magnesium is cast as molten metal. Roughly 30% of the magnesium produced in Canada is used by domestic diecasters. The remainder is exported. There are only a few (less than 10) diecasters who work with magnesium in Canada.

12.3 Emissions and Trends

In 1995, the emissions of SF_6 from magnesium production were calculated as 79 tonnes, which was the quantity reported used in blanket gas mixtures. The emission trend has been steadily downward due to continuing efforts to decrease utilization rates. However, global emissions of SF_6 are reported to be increasing at a rate of 7-8% per year. Since it has an expected lifetime of 3,200 years, it has a 100-year GWP of 23,900 making it a very potent greenhouse gas.

SF_6 Emissions from Magnesium Manufacturing

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**2000**
SF6 Emissions(t)	120	136	91	84	85	79	100
CO_2 Eq (kt)	2,870	3,260	2,170	2,010	2,040	1,880	2,390

Source: Environment Canada

Over the 1990-1995 period, while magnesium production increased marginally, SF_6 utilization rates were lowered to levels around 0.7-0.8 kg SF_6 per tonne of magnesium produced. Norsk Hydro, who account for a good portion of SF_6 usage, claims they have decreased their utilization rate to 0.64 kg/T in 1997 and are projecting a rate of 0.53 kg/T in 1998. In theory, there is a practical minimum limit in the range of 0.4 - 0.5 kg/T.

The planned doubling of capacity at Norsk Hydro will likely add another 25-30 t/yr of SF_6 emissions. The projected emissions for the year 2000 assume this extra usage.

12.4 Technologies to Reduce Emissions

There are two basic technologies for reducing SF_6 emissions from magnesium production: reducing the utilization rate; and replacement with another blanket gas.

12.4.1 Reducing Consumption

There has been continuous improvement in SF_6 utilization rates over the last few years as companies have faced significant cost pressures due to drastic price increases. Several years ago, the SF_6 market was in balance and prices were C$15-20/kg. About 3 years ago, two major producers withdrew from the SF_6 commodity business resulting in severe shortages for a period of more than a year. Prices rose to a maximum of about C$90/kg in 1996 and still range from C$30-60/kg today. This price shock has prompted companies to put in reduction methods quickly.

Increased attention to process control has allowed average concentrations of SF_6 in the inert blanket gas to be lowered from the 1% level several years ago to levels reaching as low as 0.1% at times. The key to these improvements has been the improved ability to measure minute concentrations of SF_6 at various points on the molten magnesium surface. A better system of gas injection with improved metering has been used. A control system minimizes variations. Both Norsk Hydro and Timminco report use of these process control techniques. From the Norsk Hydro utilization rate numbers, it appears that further reductions in the SF_6 utilization rate will be small, as it is approaching the theoretical minimum. There may be some opportunity to apply this process control technology to smaller diecasters who may not be as advanced as the larger producers. Reductions of 20 t/yr (10-25%) may be possible.

The cost of these systems could range anywhere from $0.5 to $3.0 million per system, depending on the number of pots controlled and the degree of distributed measurement and complexity of gas feeds. For this technology, a total cost of about $3 million for control systems for diecasters which would achieve an overall 10% reduction in SF_6 emissions has been assumed.

A second approach to reduction is the recycling of SF_6 gas. Timminco reports that some gas is recycled, but no details were provided for proprietary reasons. Norsk Hydro, as an industry leader is likely to practice some form of reuse or recycling.

Air Products and Chemicals in the US reports that they have a partnership with Dilo, a Florida recycling technology firm. Dilo extracts SF_6, purifies it and replaces it in gas mixtures. No cost information was obtained about this technology.

12.4.2 Replacement with Alternate Blanket Gas Component

In theory, any inert gas would be able to replace SF_6 if it were able to completely block out oxygen. The chemical reaction with magnesium involves the sulphur atom. Sulphur and sulphur dioxide have been identified as the most promising alternative (albeit older) technologies. The use of argon (a heavy, inert gas) is also being explored in research work, although this does not involve a chemical reaction with magnesium. The critical technology issue with the SO_2 option is how to control SO_2 emissions to protect health and odour. The capital requirements would likely include special distributed feed systems, process control systems, containment systems and pollution control systems. The assumed level of capital for this technology for the two primary producers and 5-10 diecasters is on the order of $10 million.

The reduction potential with this system would be 100%, since a complete replacement is involved. The price of SO_2 is significantly lower than SF_6, (C$440/tonne bulk SO_2 vs. C$30,000/tonne packaged SF_6), but the consumption rate will be higher. Material cost savings may result in a return of the capital invested.

12.5 R&D Capabilities and Requirements

Apart from process improvements, little direct research is taking place in Canada on this topic. Most of the magnesium research is being carried out in Norway by Norsk Hydro or in the US by gas suppliers. The suppliers of technologies are the suppliers of process control system components for measuring, controlling, and metering of gases.

Norsk Hydro is conducting research into the replacement of SF_6 gas with SO_2 at its research centre in Oslo, Norway. SO_2 has been identified as the leading alternative gas so far in the research. Argon is another gas that has been tested. The cost of the research project is bracketed at between 1 and 10 million dollars by a Canadian staff member. Norsk Hydro claims that they will definitely be replacing SF_6 gas in the future, but they don't know the timetable. Among the issues to resolve are the type of pollution control technology to protect the health of workers and the containment of the gases.

Timminco conducts some process research, but plant staff interviewed was unaware of any research into blanket gas replacements.

Air Products has experimented with another inert gas system for magnesium at their Corporate Research Center in Allentown, PA. The system is claimed to have no side effects on health and is less expensive. The main issues to resolve are the interaction of the gas with the extremely high temperature magnesium surface and containment of large volumes. A research paper is forthcoming and the contact was unwilling to reveal details.

The most promising technology for reduction is the SO_2 replacement research effort. This technology could possibly be adapted for use at diecasters.

12.6 Recommendations

It is recommended that relationships with Norsk Hydro be developed to accelerate the implementation of the SO_2 replacement alternative technology. This technology has potential to be transferred to Timminco and the smaller diecasters to help the entire magnesium sector reduce SF_6 emissions.

It appears that not all SF_6 emission sources have been accounted for, since there is a significant usage of SF_6 by utilities. Future GHG emissions inventory improvements may take this source into account.

13. HFCs and Other Uses of SF_6, PFCs

13.1 Summary

This section covers the remaining uses and emissions of the three secondary greenhouse gases sulphur hexafluoride (SF_6), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) that have not been covered in primary metal manufacture. The total estimated emissions from these three gases in other uses are about 1000 kt of CO_2 equivalents. Roughly half of the estimated emissions (500 kt) are accounted for by HFCs used in air conditioning and refrigeration applications. This area has a very high emissions growth potential with the scheduled phase-out of HCFCs by 2020.

In most HFC applications, there are several alternatives, but few which have been commercialized. Hydrocarbon refrigerants (propane and iso-butane) represent the most commonly used alternative. For SF_6 used in swichgear and cleaning applications, air or vacuum circuit breakers and better leak detection and repair programs represent the most likely technologies for reductions. For PFCs (cleaning, refrigerants and other niche uses), capture and recycle systems and substitution with lower-GWP HFEs represent current choices. There is very little research activity on SF_6 and PFCs in Canada, since most is done in the US. However, there are a few select research, testing and technical evaluation activities on alternative refrigerants which may be promising.

13.2 Background

The three types of greenhouse gases, sulphur hexafluoride (SF_6), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs), are considered as a secondary group beyond the main three naturally-occurring greenhouse gases of CO_2, CH_4 and N_2O. This secondary group has several factors in common. All gases are synthesized compounds containing fluorine, which forms very strong bonds with carbon and sulphur. Most of these gases have very high 100-year global warming potentials. The volumes of these gases used, emitted or generated tend to be much smaller than the naturally occurring gases. For most applications in this section, the majority of the volume of gases consumed are sequestered over a long time period and emissions come only from leakage losses or maintenance activities.

The major source of PFC emissions is from primary aluminum manufacturing. The major source of SF_6 emissions is from primary magnesium manufacturing. These two emission sources are covered separately in the Greenhouse Gas Emissions Inventory and have separate sections in this report. This section deals with the remaining uses of SF_6, PFCs and HFCs.

None of the three types of gases are produced commercially in Canada, all being imported from the US. Of the three types sold in commercial markets, HFCs had the highest consumption in Canada in 1995, with about 3,200 tonnes consumed. The total consumption of SF_6 in Canada is estimated at about 200 tonnes, about 80 of which is used for cover gas in primary magnesium manufacture. The consumption of PFCs in Canada is estimated at about 50 tonnes.

Summary of 1995 SF_6, PFC and HFC Use and Emissions

Greenhouse Gas	GWP	1995 Use (tonnes)	Emission Factor	1995 Emissions (CO_2 Eq - kt)
SF6	23,900			
Magnesium		80	1.0	1900 [a]
Electrical Equip.		115	0.05	140 [b]
Electronics, Misc.		5	1.0	120 [b]
PFCs	6,500-9,200	50	1.0	400 [b]
HFCs	140-11,700	3198	various	500

Source: 1995 Greenhouse Gas Inventory, CHEMinfo estimates (see sections for details)
a) discussed in another section
b) CHEMinfo Service estimates.

13.2.1 SF6 - Electrical Switchgear and Miscellaneous Uses

The largest end use for SF_6 is as an insulating gas (a dielectric) in high voltage electrical circuit interrupters or circuit breakers, generally known as "gas-insulated switchgear" or GIS. SF_6 is not used in electrical transformers. When a circuit is interrupted, the energy surge can cause an electric arc which must be quenched by the insulating gas to prevent equipment damage. SF_6 is used as an insulating gas because it has a very low dielectric constant (ε) compared to other gases. As an insulator, it has the ability to absorb high quantities of electric energy in its molecular structure and minimize the conduction of current. In substations, switchgear arrays are large, grounded, aluminum-cased cylinders which have high voltage lines running through in the centre surrounded by insulating gas. The gas is sealed inside under pressure when assembled. The use of SF_6 insulation in switchgear arrays has allowed the dense-concentration of transmission lines in urban substations having a limited ground area. If SF_6-insulated switchgear were not used, the number of high voltage lines entering a given urban substation would have to be decreased and fewer lines high voltage lines would be possible.

SF_6 has been used for this application for over 25 years. It was first developed by Japan and was used extensively in Europe from the 1970's onward. In Canada, the use of GIS become popular in the 1970's and grew substantially in the 1980's. The majority of SF_6 insulated switchgear is used in urban substations handling the junction points of high voltage transmission lines. For example, in Ontario, which has the highest concentration of high voltage switchgear in Canada, there are three voltage levels for power transmission: 500kV, 230 kV and 115 kV. SF_6 switchgear is commonly used for the 500 kV and 230 kV levels. Very little SF_6 is used in switchgear used for lower voltage distribution lines with voltages greater than 5 kV and less than 115 kV.

One SF_6 supplier estimated that about 60% of the total Canadian SF_6 market is used in GIS electrical equipment by utilities. Using an estimated total market size of 200 tonnes, as provided by a Canadian gas distributor, this volume would be approximately 120 tonnes. There are two types of use for SF_6 in switchgear: original equipment and service. Most SF_6 volume for this end use is sold directly to utility companies who assemble new switchgear prior to installation. A major supplier believes the majority of SF_6 used in electrical equipment is used for service replenishment and a minority is used for new equipment charges. A study of SF_6 use in this area has not been done publicly. The existing stock of SF_6 in Canadian switchgear may be as high as ten times the annual sales volume. This end use has characteristics similar to that of the refrigerants business: OEM sales, maintenance (replenishment) sales and a large, long-term inventory.

Utilities purchase switchgear components from major manufacturers (usually imported and under nitrogen blanket) and SF_6 is pressured into the switchgear cylinders on site. This volume is stored (sequestered) within the equipment and not emitted. The lifespan of this equipment is usually greater than 40 years. The major utilities that use high voltage gas-insulated switchgear include Ontario Hydro, Hydro-Quebec, B.C. Hydro and TransAlta Utilities (southern Alberta). There are six major international manufacturers of high voltage switchgear that would use SF_6.

Major International High Voltage Switchgear Manufacturers

Company	Country of Origin
ABB	Switzerland
Siemens	Germany
Alsthom	France
Mitsubishi	Japan
Sumitomo	Japan
Toshiba	Japan

Westinghouse also made switchgear, but it has been split into parts taken over by Mitsubishi and ABB. None of these companies manufacture high voltage switchgear in Canada. Other Canadian manufacturers of switchgear (lower voltage) include Schneider Group and Canada Power Products, both in Toronto.

Utilities also purchase SF_6 volume to replenish the insulating gas pressure in leaking equipment. The gas insulation is designed to be at a certain pressure and is periodically checked under leak detection and repair programs. Switchgear manufacturers quote standard leak rates of 1% of charge per year, which is low enough to have no significance to electrical protection. Ontario Hydro says that they are achieving better leak performance than this. Old electrical equipment is usually decommissioned by utilities and materials are recycled or treated. Gas handling carts are used to evacuate chambers and the gas is fully contained for recycle. This step is also a potential source of emissions. It is difficult to estimate the emissions of SF_6 used in switchgear. While average leak rates may be at or below 1% of total stock per year, the total stock is not known and can only be estimated. The assumption is that the total stock is five times the annual consumption (or about 600 tonnes) and that the annual emissions are 1% of this total (or 6 tonnes per year). This is equivalent to 5% of annual consumption. The 6 t/yr of SF6 represents about 140 kt/yr of CO_2 equivalents.

The leak issue has largely been an economic issue. One supplier mentioned an example of a leaking utility transformer in Canada several years ago which was not being repaired because the top-up costs are less than the maintenance costs. However, in the last 5 years, with the new knowledge of the global warming effects of the gas and the increased price, emissions from utilities are reported to have been reduced significantly, due to better equipment design and more stringent repair and capture programs.

SF_6 is imported from the US, where it is manufactured by two companies, AlliedSignal Specialty Chemicals and Air Products and Chemicals Ltd. A more detailed description of SF_6 supply is given in the SF_6 in Magnesium production section.

There are also a variety of very small volume miscellaneous uses in the electronics, analytical and medical industries. For example, SF_6 can be used as an etchant in integrated circuit board production. One Canadian distributor reports sales of one to three cylinders per year to hundreds of small companies and laboratories which account for less than 2% of total sales volume. The estimated quantity sold to this market is 5 t/yr. All use is assumed to be emitted, representing about 120 kt/yr of CO_2 equivalents.

13.2.2 PFCs

While the major emissions source for perfluorocarbons is a gaseous by-product of aluminum manufacturing, a small quantity is purchased and used in commercial markets in Canada. The main PFC compounds are: CF_4 (R-14), C_2F_6 (R-116), C_3F_8 (R-218) and C_4F_{10} (R-410). The lighter compounds have low boiling points and require very low temperatures for separation.

Most commercial uses for perfluorocarbons are in low volume niche markets. One common PFC end use is for specialty ultra-low temperature refrigerant blends, because of their low temperature properties. These blends are usually used in specialty refrigeration equipment such as cryogenic units and small-scale low-temperature environmental chambers. For example, C_2F_6 is commonly used in a azeotrope blend called R-508b, consisting of R-116 and R-23.

PFCs have already gained a strong market niche as replacements for ozone depleting substances in aerospace, electronics (plasma etching, chemical vapour deposition (CVD) and CVD chamber cleaning in semiconductor manufacturing), computer, telecommunications, medical, metal working, specialty cosmetics and other applications where high purity and cleanliness is required. PFCs have been successfully applied in Advanced Vapour Degreasing processes and are the preferred solvents for use with Teflon and other amorphous copolymers containing trifluoroethylene. Higher molecular weight PFCs such as perfluorobutane and perfluorohexane have been used to replace halons in fire extinguishing applications.

The major suppliers of PFCs include DuPont, 3M Specialty Chemicals and Air Products and Chemicals.

According to a fluoro-compound distributor to the Canadian market, the typical sales volume for these compounds is very low, about 2 lbs per sale. The total Canadian commercial volume of PFCs is difficult to estimate. One Canadian gas distributor roughly estimated no more than 10 tonnes per year. However, a 1995 estimate of PFC emissions from the US semiconductor industry was 640 tonnes. Assuming the Canadian semiconductor volume is about 5% of this figure, this segment of the Canadian market could be on the order of 32 tonnes/yr. The total Canadian market is assumed to be about 50 t/yr, all of which is assumed to be emitted. At an average GWP of 8,000, this represents about 400 kt/yr of CO_2 equivalents.

13.2.3 HFCs

Hydrofluorocarbons consumption in Canada has grown quickly over the last few years as the phase-out of CFCs has taken place under the Montreal Protocol on Ozone Depleting Substances. In 1995, the volume of HFCs consumed in Canada was 3.2 kt, but this quantity has grown from less than 1 kt only two years ago and may reach as high as 22 kt in 25 years. The following table illustrates the dynamics of the phase-outs of CFCs and HCFCs under the Montreal Protocol. The forecasts assume complete replacement of HCFC volumes with HFCs.

Estimated CFC, HCFC and HFC Use in Canada, 1990-2020

Type of Fluorocarbon	**1990**	**1993**	**1996**	**2015**	**2020**
			(kt)		
CFCs	13	8	0	0	0
HCFCs	<1	4	11	4	0
HFCs	<<1	<1	3	14	22
Total Fluorocarbons	**14**	**12**	**14**	**18**	**22**

Source: Environment Canada Commercial Chemicals Branch, CHEMinfo Services estimates

All HFCs are imported, mostly from the US. The major producers of HFCs are: DuPont (Wilmington, DE), AlliedSignal Specialty Chemicals (Morristown, NJ), ICI (UK), and Elf Atochem (France). Canadian sales are distributed through the Canadian subsidiaries of these companies, chemical distributors and refrigeration wholesalers.

About 90% of the current HFC sales volume is HFC-134a, a replacement for CFC-12. The remainder of the HFC volume is accounted for by HFC-125 and HFC-143a, two gases closely related to HFC-134a. An Environment Canada survey of HFC producers, distributors and users for the year 1995 produced the following consumption data.

Canadian HFC Consumption, 1995

	Aerosol	Foam	AC OEM	AC Serv	Refrig	Flooding	Total
Consumption (kT)							
HFC-23					0.001		0.001
HFC-32					0.000		0.000
HFC-125					0.181		0.181
HFC-134a	0.018	0.008	2.337	0.131	0.375		2.870
HFC-143a					0.106		0.106
HFC-152a	0.002				0.021		0.023
HFC-227ea						0.017	0.017
Total Use	**0.021**	**0.008**	**2.337**	**0.131**	**0.685**	**0.017**	**3.198**

Source: Environment Canada

The major end use of HFCs is as a refrigerant fluid for certain refrigeration and air conditioning applications. There are several distinct segments within the refrigeration industry where HFCs can be used. Each have their own distinct characteristics. These include the following categories:

- domestic refrigeration
- commercial refrigeration
- cold storage and food processing
- industrial refrigeration
- transport refrigeration
- room air conditioning (unitary or water chillers)
- mobile air conditioning

The dominant use of HFCs is in mobile air conditioning, where HFC-134a was unanimously selected by automobile manufacturers to replace CFC-12 in auto air conditioners. All new vehicles are now charged with HFC-134a. Existing vehicles with CFC-12 systems, when maintenance is required, are being retrofitted with HFC-134a, a process which may take years. HFC-134a has also been selected as the primary replacement for CFC-12 in domestic refrigeration in North America, South America, Asia and Australia. HFC-134a is also used in some commercial and industrial refrigeration systems for medium temperature applications, but it generally is not as efficient as HCFCs (particularly HCFC-22 and R-502 blends), which are used more often.

Only a small amount of HFCs are used as propellants in air and auxiliary blowing agents. HCFCs dominate the use in these areas. HCFC-141b is commonly used in North America as the blowing agent in rigid polyurethane foams for domestic refrigerators.

13.3 Emissions and Trends

In 1995, HFC emissions were estimated at 317 actual tonnes (equivalent to about 500 kt of CO_2). This estimation was based on sectoral usage and assumed emission factors from these sectors, as shown in the table below.

Canadian HFC Emissions, 1995

		Aerosol	Foam	AC OEM	AC Serv	Refrig	Flooding	Total
Total Use		**0.021**	**0.008**	**2.337**	**0.131**	**0.685**	**0.017**	**3.198**
Emission Factor	(kg/kg)	0.8	1	0.04	1	0.1	0.35	
HFC Emissions (kt)		**0.017**	**0.008**	**0.093**	**0.131**	**0.068**		**0.317**
Emissions (kt CO_2)	GWP							
HFC-23	11700	0	0	0	0	1	0	1
HFC-32	650	0	0	0	0	0	0	0
HFC-125	2800	0	0	0	0	51	0	51
HFC-134a	1300	19	10	122	170	49	0	370
HFC-143a	3800	0	0	0	0	40	0	40
HFC-152a	140	0	0	0	0	0	0	1
HFC-227ea	3500	0	0	0	0	0	20	20
CO_2 Eq Emissions	**(kt)**	**19**	**10**	**122**	**170**	**141**	**20**	**483**

Source: Environment Canada

OEM

The majority of HFC emissions (60%) come from air conditioning applications, including mobile and stationary sources, where HFC-134a is used. The other significant source of emissions, accounting for 29% of the total, is refrigeration, including domestic, commercial and industrial types. In each of these applications, emissions are assumed to come from leaks during OEM charging and during the life cycle, as estimated by replenishment service volumes.

HFC emissions have grown from very low levels 5 years ago as CFCs have been phased out. HFCs can be expected to continue to grow rapidly in the next 25 years as the mandated staged phase-out of HCFCs by the year 2020 under the Montreal Protocol progresses. In 1996, the first full year following the Jan. 1, 1996 phase-out of CFCs, it was forecast that there would be about 14.2 kt of fluorocarbons (HCFCs and HFCs) consumed in Canada[135]. Another forecast put the 1996 total at about 17 kt[136]. Of the first 1996 forecast total (14.2 kt), HCFC use accounted for 11 kt (77%) and HFC use accounted for 3.2 kt. There was a large conversion of CFCs to HCFCs in the years prior to 1996, but only a few select applications (e.g., mobile air conditioning and domestic refrigeration) converted to HFCs. There is potential for all of this HCFC volume to be converted to HFC use.

The consumption of HFCs could increase up to 7 times current volumes depending on how the phase-out of HCFCs takes place. In a high growth scenario, if all HCFC is replaced by HFCs and a annual growth rate of 2% is assumed, the amount of HFCs used in the year 2020 could be about 23 kt. Under this scenario, HFC emissions would be more than 7 times current levels because of the high amount of HCFCs used in rigid foam blowing (7.0 kt), which is assumed to be fully emitted. If HFCs were to be used in foam blowing, the total equivalent CO_2 emissions might reach as high as 10 times current levels, or 5,000 kt of CO_2 equivalent.

A different scenario assumes that only 50% of HCFC refrigerant use is converted to HFCs and none of the propellant and aerosol HCFC uses are converted to HFCs. The HFC use (assuming 2% annual growth) would be about 8 kt by 2020. The table below illustrates the growth potential of HFCs over the next 25 years.

HFC Use Forecast (1995-2020)

	1993	1995	2000	2005	2010	2015	2020
HCFC Reduction Target				35%	65%	90%	100%
HCFC Use (kt)		11.0	9.0	7.2	3.9	1.1	0.0
Use Scenarios:							
HFC Use (high case)		3.2	5.5	8.4	13.7	19.1	22.8
HFC Use (low case)		3.2		4.5	5.7	6.9	7.9

Source: 1996 Use Pattern Forecast and CHEMinfo assumptions

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[135] Environment Canada, Commercial Chemicals Evaluation Branch, 1996 Use Pattern Forecast for HFCs and HCFCs, Dec. 1994.

[136] Camford CPI Product Profiles, Fluorocarbons.

13.4 Technologies to Reduce Emissions

The following sections present some of the options identified to either reduce or eliminate the use of HFCs, SF_6 or PFCs. Product substitution and process modifications are the two main options for these chemicals in all application areas.

13.4.1 SF6

The alternatives identified to reduce the use of SF_6 in high voltage electrical switchgear include: leak reduction programs; air insulation systems; vacuum systems; fluid-filled (oil/paper) switchgear.

13.4.1.1 Leak Reduction

Leak reduction programs can involve several elements: improved leak detection techniques; leak sealing techniques; installing higher quality hermetic seals on switchgear components that will not degrade over time; and more rigorous leak detection and repair programs. Utilities have already improved their leak detection and repair (LDAR) programs over the last several years due to the high cost of SF_6. The potential reduction of SF_6 emissions under improved LDAR programs might be in the range of 10-50%. The cost of implementing these programs is unknown, but could be in the range of $10-40 million dollars across Canada.

13.4.1.2 Air-insulated or Vacuum Switchgear

Air-insulated or vacuum switchgear are possible substitution alternatives for certain types of substations. There is a limited use of vacuum switchgear in transmission networks, but not at 500 kV. Fifteen years ago, Ontario Hydro developed a vacuum circuit breaker at their research centre, but it was too large to be economical. Air-insulated switchgear has been used for lower voltage transmission lines (115 kV) in indoor substations but cannot be not used for higher voltage outdoor substations, because of space. With vacuum or air-insulated switchgear, the arrays are much larger and spread further apart, requiring more land space for a given number of transmission lines. For distribution voltages of 27.6 kV and lower, vacuum circuit breakers are commercially available, but very little SF_6 is used in this application. Since most SF_6 switchgear exists in high voltage urban substations, where land area cannot be expanded greatly, it is unlikely that much substitution could occur within a city. The reduction potential might be about 10-20% for this option. The cost elements for this option would include: the higher capital costs of the equipment, the cost of additional land and operating cost debits for transmission energy losses. These costs have not been quantified.

Old technology in this area employed switchgear filled with an insulating oil and paper wrapping. This technology is still used for heat insulation in transformers. The limitations on substation area also apply to this option, meaning that reduction potential is also low (10-20%). Another drawback is that line connection would have to be made with cable using an air-insulated bus (energy losses, less safe).

13.4.2 PFCs

The technologies to reduce PFC emissions include product substitutions and capture and recycling techniques.

13.4.2.1 Substitution - Hydrofluoroethers (HFEs)

The technology alternatives to perfluorocarbons are a variety of substitute products which offer similar benefits (non-toxicity, non-flammable, high solvency, high purity) but have zero ozone depletion potential and lower global warming potential. One important group is hydrofluoroethers, a family of CFC substitutes which were commercialized in 1996. 3M Company introduced HFEs, intending to replace Class I and Class II ozone depleting substances in high performance applications such as electronics cleaning, metal working, industrial processing and heat transfer. For example, the GWP of the other hydrofluoroether E-143a (CH_3OCF_3) is 360 vs. a GWP of 1300 for the structurally-similar HFC-143a (CHF_2CF_3). The GWPs of the whole family of HFEs are not known, but for this analysis, the average is assumed to be half the average GWP level of HFCs used. Thus, the reduction potential is assumed to be 50% on a CO_2 equivalent basis, based on substitution with HFEs. The preliminary per-unit cost of HFEs is US$10-15 per pound, similar to that of PFCs. The cost difference is uncertain, but small and assumed to be zero for the analysis.

13.4.2.2 Capture and Recycling

Capture and recycling systems can be used to reduce emissions of PFCs from various points in the supply chain. In manufacturing and distribution network, improved bulk loading systems reduce fugitive emissions from cylinders. At end users, systems have been developed to seal the gas under use to capture and recycle it. Gas suppliers have systems to reclaim unused gas. The reduction potential of using these systems and practices could amount to reductions of up to 50%.

13.4.3 HFCs

The following information on alternative refrigerants for vapour compression systems and "not-in-kind" technologies is summarized from the 1994 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee of the United Nations Environmental Programme (UNEP)[137]. Other information has been added for clarification or to add background. The main purpose of this report was to identify alternatives for CFC and HCFC

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[137] UNEP, 1994 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee for the 1995 Assessment of the UNEP Montreal Protocol on Substances That Deplete the Ozone Layer.

refrigerants as part of the Montreal Protocol on Substances that Deplete the Ozone Layer. The Report gives a good categorization of the global refrigerants applications and options involved. No information was obtained for alternative propellants or auxiliary blowing agents because the volume of HFC use was too small in these applications.

The alternative vapour compression refrigerants outlined here include other HFCs, hydrocarbons, ammonia, carbon dioxide, and water. Not-in-kind refrigeration technologies are defined as those which do not use vapour compression. The technologies outlined include only adsorption systems, Stirling cycles and air cycles.

13.4.3.1 Other HFCs

The choice of alternate HFCs which have lower 100-year GWPs than HFC 134a is limited to HFC-32 (GWP=580) and HFC-152a (GWP=140). The low-GWP HFC-152a has been considered by Chinese investigators as a possible alternative to HFC-134a in domestic refrigeration. However, it is flammable because it has more hydrogen in its molecular structure ($C_2H_6F_2$), whereas HFC-134a ($C_2H_4F_4$) is not flammable. Current mobile air conditioning and domestic refrigeration systems are not designed to safely handle flammable refrigerants, which pose an unacceptable safety hazard to consumers and maintenance technicians. If HFC-152a were to be used as a refrigerant in mobile air conditioners, a secondary coolant loop entering the passenger compartment may be required for safety. A secondary system would require an additional heat exchanger and fluid pump and a non-flammable coolant medium, adding to capital costs. The additional energy required adds to the total system energy requirements to the point that the total equivalent warming impact (TEWI) of HFC-152a is essentially the same as for non-flammable refrigerants. If the means were to be found to use flammable refrigerants without the need for a secondary loop, HFC-152a could provide an viable alternative to HFC-143a. Other issues for which information is not yet available include: thermal stability, chemical stability and materials compatibility.

13.4.3.2 Hydrocarbons

Hydrocarbon refrigerants have been used mostly in industrial cooling applications (e.g. lube oil dewaxing process). In the early 1990's, mixtures of propane (R-290) and isobutane (R-600a) were used in domestic refrigerators commercialized for the market in Europe, starting in Germany. The major German manufacturers include: Leibherr, Foron, Bosch-Siemens, Electrolux, and AEG. Recently, pure R-600a has been used. Nearly all new domestic refrigerators in Germany now use hydrocarbon refrigerants[138]. The use of hydrocarbon refrigerants in commercial (e.g. supermarkets) refrigeration systems with secondary cooling circuits is growing slowly in Europe, having been adopted by chains such as Migros (Switzerland), Sainsbury's, Safeway (UK), Grosso, Edeka (Germany). Denmark has announced a target ban of HFCs in all applications by 2006 by relying heavily on hydrocarbon refrigerants.

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[138] Greenpeace, The Greenfreeze Story, personal interviews

The most important issue with hydrocarbon refrigerants is the isolation of the flammable refrigerant from possible ignition sources. The European domestic refrigerator designs have the evaporators located within the refrigerator insulation, reducing the risk of leakage into the cooling compartment. Noise problems have been reported with the use of hydrocarbon refrigerants, but have been minimized with design changes. Hydrocarbon refrigerants have not been considered for use in North American design no-frost refrigerator-freezers which have electric defrost heaters in the cooling compartment along with the thin-walled aluminum evaporators.

Substantial investment costs are required at refrigeration manufacturing facilities to use hydrocarbons due to safety and purity issues. One estimate claims that an investment of about US$7 million is required to convert each plant producing 1 million appliances, some of which includes cost measures to reduce risks with cyclopentane foam blowing.[139]. Material costs are lower for hydrocarbon refrigerants. The average charge is about 25-30% of that required for HFC-134a (average of 40 gms vs 150 gms). Depending on the purity level required, the price of hydrocarbons (propane or isobutane) is about 25-50% of HFC-134a (US$10-20 vs US$40/lb). Hydrocarbon refrigerators are more energy efficient than those using HFC-134a, so energy consumption over the lifetime is less. Hydrocarbon compressor costs may be slightly less expensive than HFC compressors, due to design and the fact that special ester lubricating oils are nnot required. HC refrigerators in Europe are reported to be comparable in cost to HFC refrigerators. The UNEP Technical Options Committee expects that hydrocarbon units will have a 30% share of the worldwide domestic refrigeration market by 1999, mostly in Europe and developing nations. The development of propane unitary air conditioners may be slower, due to costs which are 30% higher than HCFC-22 units.

European safety standards currently allow up to 150 gms of hydrocarbon refrigerant to be used in domestic refrigerators. Current North American ASRAE[140] standards do not allow the use of any flammable refrigerants in domestic systems. Many refrigeration experts consider the severe legal liability environment in North America to be a high barrier for acceptance of flammable refrigerants. The liability laws are far less strict in Europe. The standards are currently under review to allow the blending of flammable and non-flammable refrigerants. The intent of the review is to achieve a limit of up to 150 gms of flammable fluid in a refrigeration system, while still ensuring that the refrigerant mixture is not flammable. If the ASHRAE standards are modified, the CSA would likely follow and could permit the use of hydrocarbons in mixtures in refrigeration systems.

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[139] Ozone Operations Resource Group (OORG), World Bank Global Environment Coordination Division, 1993

[140] American Society of Refrigeration and Air Conditioning Engineers

13.4.3.3 Ammonia

Ammonia is an inexpensive commercial chemical which is both toxic and flammable. Its toxicity is the major issue regarding its use. It is principally used in large scale refrigerated warehouses and arena ice-rink freezing systems where the major equipment is installed is isolated in a location not normally associated with public occupation. Ammonia is used in 81% of refrigerated warehouses in the US and about 60% of cold storage and food processing systems in Germany. To use ammonia in smaller systems, secondary cooling circuits (using non-toxic, non-flammable fluids) would likely have to be applied to overcome toxicity concerns, at significant extra cost. The technical issues for the use of ammonia include the development of hermetic compressors and new lubricants providing solubility in ammonia to enhance heat transfer surfaces for heat exchange tubes (e.g. poly-alpha-oleofin and poly-alpha-glycol oils). Other barriers include the review of health regulations and building codes.

13.4.3.4 Carbon Dioxide

Carbon dioxide refrigeration systems are similar to conventional vapour compression systems, but operate at compressed pressures 4-5 times higher than fluorocarbon systems (1500 psi vs 300-375 psi) due to the low critical temperature of carbon dioxide. They are currently under consideration as possible alternatives for stationary and mobile air conditioning systems. The main issues are the impacts of the high pressures on: safety, design of equipment (cost), compressor performance, refrigerant containment and long-term reliability. An operational concern is the ability to condense the fluid at high ambient temperatures in hot climates. Carbon dioxide systems have not yet been studied on real vehicles under actual operating conditions.

13.4.3.5 Water/Zeolite Adsorption Systems

Water/zeolite adsorption systems are sometimes referred to as dessicant systems. The refrigerant fluid is water and two solid zeolite (an alumina silicate matrix having a unique lattice structure) dessicant beds are used to alternatively adsorb and desorb water vapour. Instead of using a mechanical compressor to increase refrigerant pressure in the cycle, heat is used to desorb water into vapour. Subsequently, heat is released when the water is re-adsorbed into the solid.

Adsorption systems have been proposed for residential heat pumps and mobile air conditioners. These systems require a source of either direct or waste heat. With the current designs of energy-efficient automobiles with catalytic converter systems, the source of waste heat is limited. German car manufacturers reported that there is insufficient surplus of energy available to drive such a system during idling, city traffic and below cruising speeds of 60 km/h and that diesel engines provide no surplus energy under any conditions. Water/zeolite systems appear to have limited potential in some larger truck and bus air conditioning systems where the heat source is larger.

13.4.3.6 Stirling Cycle

The Stirling refrigeration cycle is based on the principle that at a constant volume, a gas rises in pressure when heated. The refrigeration systems use an external Stirling unit and hydrogen or helium gas as the refrigerant. The system efficiency is improved when the inside/outside temperature difference is higher. Generally, prototype Stirling systems are less efficient than fluorocarbon or hydrocarbon vapour compression systems operating at normal conditions for household refrigeration or air conditioning.

Further developments to improve system reliability, reduce high component costs, reduce auxiliary power requirements (fans and blowers) and improve heat transfer between cooled area and the Stirling unit are required before commercialization can be considered possible.

13.4.3.7 Air Cycle Systems

Air cycle refrigeration uses the expansion of compressed air to provide cooling. The air cycle technology requires a high-speed, highly efficient turbo-compressor/expander unit coupled with high efficiency heat exchangers and possibly two stages. Since the system efficiency drops drastically with decreased compressor speed, an energy efficient method must be developed to control the system when full cooling is not required.

This system is used on aircraft where a source of compressed air is available from the turbine engines. Some pilot applications are expected before the year 2000 for transport trucks and railway refrigeration and air conditioning. Significant developments are still needed in efficiency and cost effective turbines/compressor constructions. The European Union has funded a 3-year research project (Joule II) to develop air cycle heat pumps, air conditioning and refrigeration systems for specific applications.

13.4.3.8 Costs to Reduce HFCs

Any number of these technologies can be combined to reduce HFC emissions from refrigeration systems. Partial reductions can take place through substitutions in certain segments, as in the example of the domestic refrigeration segment in Europe, where over 80% of HFC refrigerants have been substituted by hydrocarbons. It is technically feasible to completely eliminate all HFC refrigerants in all segments although the economic analysis is quite complex. When the ozone depleting substances (CFCs, halons) were scheduled to be eliminated under the original Montreal Protocol, a 1988 Canadian socio-economic cost-benefit analysis was performed. The results showed that the range of total costs (social costs plus transfer costs) of eliminating ODS had net present values (using a discount rate of 7.5% over 80-years) of between $200 and $300 million[141]. When the Copenhagen Amendment to the Montreal Protocol came into force, accelerating CFC reductions, a 1993 socio-economic analysis concluded that the total cost of substitution has a net present value (7.5% over 45 years) of $270 million[142]. In a third socio-economic analysis in 1995, performed on the impacts of reducing HCFC consumption under the Copenhagen Amendment schedule, the total cost of substitution had a net present value (7.5%

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[141] Abt Associates of Canada, Socio-Economic Impact Assessment of Implementing the Montreal Protocol on Substances that Deplete the Ozone Layer., August 1988.

[142] Abt Associates of Canada, Socio-Economic Assessment of Amendments to Regulations Related to Ozone Depleting Substances, May 1993.

over 45 years) of $340 million[143]. The cost models used for these studies were based on demand curves developed by US EPA engineering studies on cost alternatives, and correspond to replacement of approximately 14 kt of chemicals. While the new alternatives to HFCs have yet to be costed and may be more expensive than the alternatives used for CFCs halons and HCFCs, these studies give an order of magnitude estimate for the cost level involved. The assumption is that the listed alternatives are more expensive than the HFC options used in these socio-economic studies (due to extra health and safety protection costs). Therefore total present value costs (including capital and operating) to eliminate nearly 3 kt of HFCs used in 1995 might be in the range of $100 to $200 million. Obviously, by the year 2010 when HFCs will dominate the market, this cost will be much higher.

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143 Abt Associates of Canada, Socio-Economic Impacts of Reducing Consumption of HCFCs by Allocating Transferable Allowances to Producers and Importers., March 1995.

Summary of Alternative Refrigerant Technologies to Reduce HFC Emissions

Refrigerant	GWP	Advantages	Disadvantages
Other HFCs	140-11700	commercialized (mobile AC, domestic refrig. in N. America); high efficiency; some have low GWPs (e.g. 140-650); non-toxic; non-flammable; excellent thermodynamic properties	most have moderate GWPs; some alternatives flammable (e.g. HFC-152a with GWP of 140)
Hydrocarbons	low	commercialized (domestic refrigeration Europe); low GWP; high efficiency; excellent thermodynamic properties	flammable; mixtures difficult to optimize; some noise problems reported; secondary cooling usually required
Ammonia	0	commercialized (warehouses); zero GWP; excellent thermodynamic properties	toxic; flammable in some conditions; material incompatibilities
Carbon Dioxide	1	GWP of 1.0; non-toxic, non-flammable; well-known properties	very high pressures required; low efficiency; high equipment costs
Water	0	negligible GWP; widely available at no or low cost; non-toxic; non-flammable; high efficiency	low suction pressure; high volumetric flow rate; large compressor (3-8 times conventional); high comp. costs
Water-Zeolite Adsorption	0	tested on A/C in trucks and buses; zero GWP; possible high heating efficiency; can use waste heat if captured	low cooling efficiency; very large systems required; high equipment costs
Stirling Cycle with H_2 or He	0	prototypes developed; applied to cryogenic systems; zero GWP; theoretical high efficiency; wide temperature range	low demonstrated efficiency; uncertain long term reliability; high unit costs; auxiliary energy for pumps/fans for secondary heat transfer required
Air Cycles	0	zero GWP; immediately available; high reliability	low efficiency; not economically feasible in many applications

Source: UNEP, 1994 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee

13.5 R&D Capabilities and Requirements

Very little research activity is taking place in Canada in the areas of SF_6 and PFC reduction technologies. There is, however, some activity on development of alternative refrigerants for HFCs. This section describes the major participants and activities that were found to be taking place in Canada.

13.5.1 SF6

The major Canadian utility companies would be directly involved in managing the reduction of SF_6 emissions from high voltage switchgear. Ontario Hydro, which claims it is, by far, the largest user of gas insulated switchgear in Canada and perhaps North America, has not done any direct research in this area for the last 4-5 years. Ontario Hydro operates Ontario Hydro Technologies, a central research facility in Etobicoke, ON. In early days, research was done to manage technical, safety and environmental problems with the use of SF_6. For example, the aging of SF_6 with increased exposure to electrical discharges was studied. The only current work done by technical staff at the research centre in this area is to monitor the concerns about SF_6 emissions.

Other important utility research centres in Canada include Hydro-Quebec's Institute Recherche de Hydro Quebec in Varennes and B.C. Hydro's Central Lab Powertech in Vancouver.

The recommended research in this area is to look at gas management issues, including detection of leaks, recycling techniques, and reuse. Little work has been done on prevention of leaks from switchgear equipment. One example of work that could be done is to test and improve technology developed in the US to measure low concentrations of SF_6 gas. An infrared backscatter detection technology was developed and is thought to be very promising in picking up very small leaks.

Most of the work on SF_6 in electrical equipment is being done in the US. Three research centres were cited by Ontario Hydro Technologies:

1. Oak Ridge National Laboratories (Oak Ridge, TN - funded by the US Dept. of Energy)
2. National Institute of Standards and Technology (NIST) (Gaithersburg, MD - funded by US Department of Commerce)
3. The University of Tennessee

13.5.2 PFCs

No information was identified on PFC research activities in Canada. Research activities on substitutes for PFCs in semiconductor cleaning will be concentrated at the research facilities of 3M Specialty Chemicals (St. Paul, MN), and DuPont (Wilmington, DE), the major suppliers of PFCs.

In October 1993, the US EPA Climate Change Action Plan called for restriction in use and emissions of high GWP chemicals by encouraging product stewardship and using the Clean Air Act Amendments of 1990 to narrow uses of CFC substitutes such as HFCs and PFCs. The EPA called for a partnership program with manufacturers of HFCs and PFCs in which the companies would commit to "reducing use of these gases and ensuring that users handle the material in an environmentally responsible manner, by capturing and destroying the gas rather than emitting it to the atmosphere."

DuPont, the largest manufacturer of C_2F_6 and HFC-23, issued a policy statement in February 1996, which stated:

> "Recognizing DuPont's goal is to avoid significant accumulation of PFCs in the environment, DuPont will sell ZYRON R 116 (C_2F_6) only to those end users and distributors who have a program to minimize PFC emissions and who have a philosophy of zero emissions as their ultimate goal. DuPont will seek more environmentally acceptable alternatives to PFCs. If, through these collaborative activities, DuPont concludes that it is unlikely that solutions which significantly reduce ZYRON R 116 emissions will be developed, selected and under implementation by year-end 1999, we will notify end users and distributors of our assessment and, in consultation with them, develop our plans to phase out supply of ZYRON R 116."

The other major manufacturer of PFCs is 3M Specialty Chemicals. 3M makes C_3F_8, the newest PFC to be used by the semiconductor industry. The company's Policy Statement declares:

> "3M Specialty Chemicals will fully support and actively participate in the technical developments needed to attain the PFC emission reduction objectives of the semiconductor industry. 3M is fully committed to environmental stewardship and the mitigation of future environmental concerns associated with PFC use; 3M offers its expertise to assist PFC users in understanding and implementing PFC product stewardship practices that are technically and economically feasible; 3M is working with distributors and other partners in the semiconductor industry to provide manufacturers with PFC product-use and emissions reduction support; 3M is actively working with international and domestic regulatory bodies to advance global adoption of responsible PFC use and emissions reduction policies that are technically and economically feasible and are based on sound scientific analysis."

Praxair, one of the largest gas distributors in the world, has implemented several measures to reduce PFC emissions. A modern bulk filling system has been installed in Arizona which reduces cylinder transportation and emissions from filling operations. The company has introduced a patented method of recovering and reprocessing remaining product in returned cylinders. A partner of Praxair, EcoSys (division of Advanced Technology Materials (Danbury, CT) has developed several types of abatement equipment specifically designed to eliminate PFC emissions at smaller users.

Halozone Technologies is a Toronto company set up in the last 5 years which markets technology systems to capture and recycle CFCs, halons, HCFCs, HFCs and PFCs.

The US EPA has signed a Memorandum of Understanding with 18 semiconductor manufacturers called the "The PFC Emission Reduction Partnership for the Semiconductor Industry." This MOU requires semiconductor manufacturers to measure their PFC emissions and reduce the 1995 normalized emissions rate (emissions/output) through recycling, abatement, more efficient use and chemical substitution. This MOU would likely apply to Canadian operations.

13.5.3 HFCs

An Expert Panel has been established by Environment Canada to review alternatives to CFCs and HCFC-22 used in refrigeration, air conditioning sector, to identify the most promising ones, and to provide recommendations on how to facilitate the development or introduction of such alternative refrigerants and technologies.

The Expert Panel will be chaired by the National Research Council (NRC) and will be composed of four independent experts all with background and relevant experience in the application of alternative refrigerant technologies. The Panel will receive input regarding up to 85 alternative technologies from a broad cross-section of stakeholders in Canada and evaluate proposals against reference cases using Total Equivalent Warming Impact (TEWI) analysis by computer simulation techniques. Promising alternatives will be reviewed for their technical and economic feasibility. Environmental, health, safety and regulatory issues will be reviewed and recommendations made. Three reports will be prepared: Residential (June 1998), Commercial (Feb. 1999) and Industrial (June 1999).

It appears that very little direct research on HFCs alternatives is taking place in Canada. Several industry sources report that any HFC research by major producers is being carried out in their US research centres. For example, DuPont is a major supplier of HCFCs and HFCs. It reports that all its research is taking place in Wilmington, DE. In the past, the only Canadian research activity DuPont Canada undertook was to sponsor research programs at the University of Fredericton and University of Moncton. They have carried on no direct research in Canada.

Some significant research on alternatives is being carried out by Dr. Samuel Sami of the University of Moncton. He is exploring two "not-in-kind" refrigeration technologies: absorption systems and adsorption systems. Both systems use waste heat as the driving force for the vapour compression. The first system uses a natural material which absorbs water. The waste heat acts to desorb the water forming a "chemical compressor" which is driven by the concentration of the fluid absorbed. The second system is a desiccant system using a solid with water to generate comfort cooling for air conditioning applications. The system uses a desiccant stored in a rotating wheel through which the waste heat stream flows. The water is alternatively absorbed and desorbed through the cycle. Other research involves the performance measurement of HFC blends (new blends from major producers and those developed internally). Dr. Sami describes his research as unique in North America.

At University of Fredericton, the work of Dr. Vernard explored the measurement of certain thermophysical properties of fluorocarbon refrigerant blends and the use of HFCs as fire retardant agents.

At UBC, Dr. Dan Fraser of the Mechanical Engineering Dept. is conducting research into evaporator and condenser heat transfer performance for alternative refrigerant fluids. The Alternative Refrigerant Research Facility has been set up in the last three years to study new refrigerants in forced convective boiling. The research work is just starting to produce data. The purpose of the research is optimize refrigeration heat exchanger system design to improve operating efficiency and reduce the cost of replacing existing systems. Dr. Fraser believes that the alternative refrigerant evaluation facility is one of the best equipped facilities of its kind in North America. The scope of work is similar to that being conducted in the US by major refrigerant companies like Dow and DuPont, but encompasses a broader family of refrigerant products.

Dr. Fraser is also conducting fundamental research into heat pump applications which utilize natural sources of heat. Heat pumps operate on the same principle as refrigeration cycles, but the purpose is to extract heat from a natural source and transfer it to another location via a working fluid in a vapour compression cycle. The heat sources being considered include: the ocean, geothermal sources and wastewater effluent. Heat sinks might include office buildings and institutions. These types of systems are in advanced stages of development (and use) in Europe, particularly in Scandinavia.

At McMaster University, Dr. Mamdo Shoukri, the Dean of the Faculty of Engineering is studying the fluids mechanics and flow visualization of HFC-134a refrigerant.

Greenpeace International are facilitating an initiative to explore the investment potential of a hydrocarbon refrigerator factory in Quebec. Greenpeace is acting to bring interested parties together. The parties are include a Quebec Trade Union Fund and a Chinese Refrigerator manufacturer.

Other minor Canadian initiatives mentioned by Greenpeace include:

- a Canadian water cooler manufacturer (working with Calor Gas, UK) is in the process of converting production to hydrocarbon refrigerants in the next few months.
- pop machines being sold in Canada using hydrocarbon refrigeration technology developed by a Danish company and the German manufacturer Electrolux.

13.6 Recommendations

Given the expected growth of HFC's as replacements for HCFC's, it is important to support technology development in this area. While chemical suppliers have a vested interest and are quite active in the field, there are many niche development positions for Canadian participation. Some of the activities that can be supported include:

- Research into HFC alternatives at universities should be supported. The work of the NRC Expert Panel will provide some guidance on priority areas in refrigeration applications over the next two years.
- There is an opportunity to support research at major utility companies to improve SF_6 leak detection and repair techniques. This activity may be in conjunction with technologies to capture and recycle PFC and SF_6 emissions from the electronics industry.

This section has provided a rough estimate of use by application and emissions for each of HFCs, SF_6 and PFCs, but the data needs to be refined. A more detailed study identifying applications and related emissions of SF_6 and PFCs is recommended to improve the problem identification in this area.

14. Carbon Sequestration in Biomass

14.1 Summary

Upwards of 25-30 different forest management practices that are available to sequester carbon (C) in Canada's biomass. The most common of these practices are reforestation of previously stocked land, afforestation of land that has historically not been forested, and the use of forests as a bioenergy source to offset fossil-fueled based GHG emissions. (α)

Extensive work in this field has determined that many forest management practices are among the most cost-effective tools in which countries can meet their respective GHG emissions target. Many reforestation and afforestation cost estimates are in the range of $5 to 15 per tonne of CO_2 removed. Depending on various forest management scenarios, and the amount of land addressed carbon dioxide reductions of 1% to 145% of Canada's total annual carbon dioxide emissions (461,000 kilotonnes in 1995) can theoretically be achieved. As a reference point, the costs to achieve 13,400 kilotonnes of emission reductions annually (i.e., 3% of total emissions), would cost approximately $134 million annually (@$10 per tonne-CO_2).

The potential for forest management practices to sequester carbon is quite significant. Work to date has determined that many different practices currently available are proven and cost effective. Given the large land mass in Canada, the significant amount of land that is available to be used for reforestation as well as the various preservation practices that can be employed, Environment Canada (in conjunction with the CFS) would be well suited to undertake additional research on where the greatest potential lies, both in terms of actual forest management practices to employ as well as the geographic location to concentrate this activity.

14.2 Background

Canada has a large amount of biomass contained within its borders. For instance, forests cover approximately 42% of Canada's land mass and Canadian forests represent approximately 10% of the Earth's forested area. Of Canada's total forested area, approximately 82% is in the boreal forest zone and 18% in the temperate zone.

Canada's Forested Lands

Land Category	Area (million ha)
Total Area	997.1
Land Area	921.5
Forest Area	417.6
Timber-productive forest land	244.6
Timber-productive nonreserved forest land	235.6
Stocked timber-productive nonreserved forest land	218.4

Source: Canadian Council of Forest Ministers, *1996 Compendium of Canadian Forestry Statistics*, pg. vi.

With such a large land mass and forested area, the forest sector is one of Canada's leading economic sectors, contributing 3.0% to Canada's economy annually and employing approximately 360,000 people directly.

Economic Profile of the Canadian Forestry Sector

Economic Profile	($ billion)
Value of Shipments	$58.7
Value of Exports	$32.7
Balance of Trade	$27.4
Capital and Repair Expenditures	$7.1
Employment (direct jobs)	358,000 persons
Contribution to the economy	3.0%

Source: Canadian Council of Forest Ministers, *1996 Compendium of Canadian Forestry Statistics*, pg. vii.

14.3 Emissions and Trends

Biomass (i.e., forests) is both a source and a sink for CO_2. As a sink, biomass withdraws CO_2 from the atmosphere through photosynthesis. CO_2 is also returned to the atmosphere by the respiration of vegetation and the decay of organic matter in soils and litter. The total flow of CO_2 is significant (i.e., roughly 1/7th of total atmospheric CO_2 passes into vegetation annually). Biomass CO_2 emissions originate from both anthropogenic (e.g., combustion of wood for energy, combustion and landfill decay of wood and other biomass wastes, prescribed burning, human and animal respiration, and fermentation of wastes) and natural (e.g., wild fires and decay) sources.[144]

Without anthropogenic intervention, the large flows of CO_2 from the atmosphere to the terrestrial biosphere are balanced by the return respiration flow. In other words, biomass would neither be a source or a sink of CO_2 as the respective flows would offset each other. However, human intervention (e.g., altering land use or the use of forests) directly impacts these fluxes and therefore the amount of carbon stored in living vegetation, litter and soils.

A forest carbon budget incorporates four major carbon pools or reservoirs: forest biomass; forest soils; peatland soils; and forest products resulting from our use of forest resources (e.g., building materials, wood products, paper, etc.). Carbon stored in Canadian forests is estimated to be approximately 221 Gt C, delineated as follows: [145]

- 14.5 Gt C in standing forest biomass (trunks, branches, roots, etc.);
- 70.6 Gt C in forest soils;
- 135 Gt C in peatland soils; and
- 0.6 Gt C in forest products.

The Canadian Forestry Service (CFS) has estimated that averaged between 1920 and 1990, the Canadian boreal and subarctic forest was a carbon sink of 118 million tonnes of carbon (Mt C) per year. However it is important to note that although Canada's forests have been a sink for much of this 70 year time period, the amount of CO_2 that is sequestered annually has declined continually since the early 1970s. Another major finding from the work of the CFS is that the boreal and subarctic forests in Canada abruptly became a source for atmospheric carbon during the 1980s, averaging 57 Mt C/yr (in other words, Canada's forests have now become a net source of C emissions instead of a net sink).

Carbon Budget of Canadian Forest Sector From 1985-1989

Carbon Pools	Sink	Source	Transfer	Net Change
	(Mt Carbon)			
Forest Biomass	33	-26	-86	-80
Forest Soils	36	-17	-	19
Forest Products	50	-27	-	23
Peatlands	26	-	-	26

Source: Environment Canada: *Trends in Canada's GHG Emissions 1990-1995.*

Note: Positive numbers represent increases in carbon pools, negative numbers represent releases to the atmosphere or transfers to other carbon pools.

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[144] Jaques, A., et al, "Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)", Environment Canada, April 1997., pg. 55.

[145] Ibid, pg. 57.

There are two major reasons for Canadian forests changing from a net sink to a net source of carbon: (i) increase in the amount of fires occurring; and (ii) increase in insect disturbances. Harvesting appears to have played only a minor role in this abrupt change from sink to source.[146]

However, there are opportunities to reverse this trend. Work undertaken in this field has indicated that by the anticipated time of doubled atmospheric CO_2 (probably between the year 2050 and 2100), managing the world's vegetation could turn the terrestrial biosphere from a source of carbon (likely range: 4.2 Pg C/yr source to 1.3 Pg C/yr sink) to a carbon sink (likely range: 0.1 Pg/yr source to 3.0 Pg/yr sink).[147]

14.4 Technologies to Sequester CO_2 in Forests

Many different technologies and management practices can increase the ability of forests to sequester carbon or offset energy related GHG emissions. Generally these options can be segmented into one of three categories:

- increase carbon storage of forests;
- maintain carbon storage and therefore avoid carbon emissions; and
- reduce energy related carbon emissions.

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[146] Ibid, pg. 58.

[147] Richards, Kenneth R., Alig, Ralph., Kinsman, John D., Palo, Matti., Sohngen, Brent., Consideration of Country and Forestry/Land Use Characteristics in Choosing Forestry Instruments to Achieve Climate Mitigation Goals, pg. 1.

Land Use and Forestry Practices to Manage Carbon

	Major Objective		
Practice	**Increase C Storage**	**Maintain C Storage Avoid C Emissions**	**Reduce Energy C Emissions**
Afforestation	x		
Agroforestry	x	x	x
Breeding/genetics	x	x	
Biomass for energy			x
Disease control		x	
Drainage	x		
Fertilization	x		
Fire control		x	
Herbivore control		x	
Improved regeneration	x		
Increased forest products	x	x	x
Insect control		x	
Irrigation	x		
Longer rotation	x	x	
Preservation		x	
Recycling		x	x
Reduced impact logging		x	
Reforestation	x		
Salvage dead biomass		x	
Shade trees			x
Shelterbelts		x	x
Soil management	x	x	
Stocking control			
Thinnings	x		
Enrichment Plantings	x		

Source: Richards, Kenneth R., Alig, Ralph., Kinsman, John D., Palo, Matti., Sohngen, Brent., *Consideration of Country and Forestry/Land Use Characteristics in Choosing Forestry Instruments to Achieve Climate Mitigation Goals*, pg. 2.

It has been estimated that forestry and related land use measures could reduce net U.S. CO_2 emissions by 10-15%.[148] Considering that Canada has lower overall emissions vis-à-vis the United States and that our forest and land area is larger, the importance of proper forest management practices is clear. A brief summary of the carbon sequestration potential of various forestry management measures is shown below. More detailed descriptions of some of these practices follows in this section.

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[148] Trexler, Mark., Minding the Carbon Store: Weighing U.S. Forestry Strategies to Slow Global Warming. World Resources Institute, Washington D.C, 1991.

Opportunities to Increase Annual Carbon Storage and Reduce Emissions Through Forestry, Tree, and Wood Use Programs

Opportunity	**Average Annual Increase in Carbon Storage (US Results)**	
	Low Estimate	**High Estimate**
	(million tons)	
Converting marginal crop and pasture land to forests	36	131
Increasing timber growth on timber land	152	210
Growing short-rotation woody crops for energy	100	199
Increasing tree numbers and canopy cover in urban areas	12	38
Planting trees in shelterbelts	3	7
Total all opportunities	**303**	**585**

Source: American Forests, *Forests and Global Change, Volume II.*

There are several advantages of using forests as a management tool for reducing net carbon emissions:[149][150][151]

- many different management practices can be deployed and the overall CO_2 sequestration and storage potential is very large;
- forest management practices can result in significant ancillary benefits associated with soil conservation, watershed management, biodiversity conservation, and sustainable rural development;
- the costs of carbon uptake for various forest management practices are generally well documented, more so than for many other options;
- land use based mitigation measures can be among the most cost-effective climate change mitigation options;
- forest sector strategies are easily reversible; and
- forest biomass can substitute for fossil fuels, while forest products can replace products made from cement, plastics and so on, which have larger contributions to global warming.

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[149] Trexler, Mark., Considerations in Forecasting the Demand for Carbon Sequestration and Biotic Storage Technologies, pg. 7-8.

[150] Van Kooten, G., Cornelis, Grainger Alan, Ley, Eduardo., Marland, Gregg., Solberg, Birger, Conceptual Issues Related to Carbon Sequestration: Uncertainty and Time, pg. 12.

[151] Trexler, Mark., Considerations in Forecasting the Demand for Carbon Sequestration and Biotic Storage Technologies, pg. 2.

Another significant advantage of forest management practices is that they can potentially assist a country in maintaining a strong growth objective and yet still address climate change issues. This allows countries to not significantly reduce fossil fuel use while still contributing to the solution for global climate change. Policies that conserve existing forests or result in tree planting to increase the country's annual carbon sequestration rate allows countries to "buy time", while they continue to search for technological solutions that have less drastic effect on the national economy.

14.4.1 Reforestation and Afforestation

This management practice essentially involves planting and maintaining new forests. Reforestation infers that forests will be planted on lands which previously had forests located on them while afforestation refers to planting forests on land which have traditionally not been occupied by forests. Research has revealed that there are large amounts of land that are potentially available for reforestation in both temperate and tropical zones.[152] The availability of land in tropical zones is of interest to Canadians as it offers potential joint implementation opportunities to be operationalized in conjunction with developing countries. Xarieties of reforestation/afforestation activities available include:

- pasture, cropland, degraded or arid land reforestation;
- reforestation of recently harvested stands;
- planting along highway rights-of-way and riparian corridors; and
- planting in windbreaks and other argoforestry applications.

Reforestation/afforestation projects appear to be one of the more cost-effective ways to increase terrestrial carbon storage. Several countries are considering or have implemented tree planting programs as one element of their climate change action plan.[153] For instance, the Noordwijk Declaration of December 1989, signed by 68 environment ministers from around the world, proposed increasing global cover by 12 million hectares per year (starting in 2000) to help slow climate change. In addition, the U.S. Climate Change Action Plan has proposed to support the U.S. Department of Agriculture in planting over 800,000 acres of trees on non-industrial private forest lands by the year 2000.

The credibility of reforestation has been well documented with one of the contributing factors being that sequestration benefits of reforestation are relatively easy to measure and verify. However, the persistence of the CO_2 emission reduction benefit can vary widely for different types of reforestation, as can the timing of the benefits.

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[152] Ibid, pg. 5.

[153] Sampson, Neil, Sedjo, Roger A., Wisniewski, Joe, Economics of Carbon Sequestration in Forestry: An Overview, pg. 4.

Carbon Emission Sequestration from Afforestation Activities in the U.S.

	Converting Cropland to Forest			Converting Pasture to Forest		
	Years	**Ft^3/acre/yr**	**Lb/acre/yr**	**Years**	**Ft^3/acre/yr**	**Lb/acre/yr**
Region and Forest Type	Cutting Period	Growing-Stock Volume	Carbon Storage	Cutting Period	Growing-Stock Volume	Carbon Storage
Northeast						
White/red pine	65	34.8	2,854	65	34.8	3,018
Spruce-fir	80	27.4	2,460	80	27.4	2,508
Maple-beech-birch	80	31.8	2,850	80	31.8	2,925
North Central						
White/red pine	80	85.0	4,344	80	85.0	4,376
Spruce-fir	80	20.6	1,979	80	20.6	2,019
Maple-beech	80	30.2	2,531	80	30.2	2,566
Pacific Coast						
Douglas-fir	80	215.2	6,657	80	168.0	5,470
Pondersoa Pine	100	46.1	2,071	100	46.1	2,065

Source: American Forests, *Forest and Global Change, Volume I - Opportunities for Increasing Forest Cover.*

Harvesting and then implementing a reforestation program has also been suggested as a management option that is available to increase carbon sequestration. The theory behind this practice is that old growth forests (which may have large stocks of carbon) may only be able to sequester small or negligible amounts of carbon, since net biomass growth is modest or negligible. Alternatively, a young forest may have a relatively modest stock of carbon due to its small total biomass, but at the same time generate substantial flows into that stock due to the rapid growth of juvenile trees.[154]

Growing trees for C storage may be more appropriate on land with low productivity or where the biomass cannot be harvested. In turn, on high productivity land, the more cost effective strategy is to manage the forest for a harvestable crop and to use the harvest for maximum efficiency by ensuring that the wood is used in long-lived products or is used to substitute for fossil fuels.[155]

14.4.1.1 Costs to Reduce

Tree planting programs incur a variety of costs. For instance, establishing a plantation usually involves an initial substantial investment (e.g., land cost, land preparation, actual planting, etc.) followed by 4 or 5 years of additional expenditures. Following this investment, only custodial activities are required for the remainder of the forest life. It should be noted that custodial costs

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[154] Ibid, pg. 1.

[155] Organization for Economic Cooperation and Development, Policies and Measures for Common Action - Working Paper 7 - Agriculture and Forestry, Identification of Options for Net GHG Reduction, pg. 39.

usually rise with the age of the forest because the forest becomes more susceptible to disease, fire, etc.[156]

There has been extensive effort within the forestry economics community to quantify the costs (in terms of dollars per ton) of sequestering carbon through tree planting. A great majority of these studies have estimated a relatively low carbon sequestration cost, usually in the C$17/tonne-C (\$5/tonne-CO_2) and not often reaching over C$50/tonne-C.[157] For instance, Winjum et al. (1992) estimated that the costs of sequestering carbon on a massive worldwide scale for a range of countries. These results estimated the range would be from less than $1 to about $11 per ton of carbon sequestered, depending on the country. In terms of carbon offsets (i.e., joint implementation projects), other studies have estimated the expected cost would vary from C$1 to $50/ton for projects proposed by major US and European utilities.[158]

Average Annualized Cost of Sequestering Carbon

(Selected Cases) (C$/tonne)

	Tropical		**Temperate**	**Boreal**	
	Agro-forest	**Plantation**	**Plantation**	**Plantation**	**Protection**
Andrasko (1991)	5-8	5-10	0-4		
Dixon et al. (1993)	7-25	10-100	4-80	5-40	1-7
Krankina and Dixon (1993)			1-10	1-13	1-5
Houghton et al. (1991)	5-20	7-60			

Source: Sedjo, Roger A., et al, *Managing Carbon Via Forestry: Assessment of Some Economic Studies, Discussion Paper* - Resources for the Future.

It should be observed that forest protection sequestration costs are also outlined in the above table. These costs are substantially lower than the costs of actually planting trees. This should be expected as the primary sequestration cost of forest protection is the cost of purchasing the land. Tree-planting costs which are not incurred in forest protection are in reforestation and afforestation management options. More information on forest protection is provided later in this section.

The earlier work (see table above) in estimating carbon sequestration costs provided only single point estimates, and thus do not represent the very real problem of rising costs that are associated

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[156] Sedjo, Roger A., et al, Managing Carbon Via Forestry: Assessment of Some Economic Studies, Discussion Paper - Resources for the Future, pg. 5.

[157] Ibid, pg. 9.

[158] Ibid, pg. 8.

with involving large land areas. In other words, it is expected that the cost per ton of carbon sequestered would become more expensive as more and more land is reforested or afforested. The marginal costs for large-scale carbon sequestration projects would be expected to rise because of:[159]

- increasing land opportunity costs;
- varying land productivity for tree growing and thus low biological growth rates and associated low rates of carbon sequestration; and
- perhaps the rising costs of other inputs.

The work being undertaken currently is more involved as these studies have developed a cost function, rather than a simple point estimate, that estimates the rise in costs of capturing carbon associated with large scale tree planting.

Estimates of Cost of Carbon Sequestered by Tree Planting: Some Comparative Results for the U.S.

	Total Carbon Sequestered (million tonnes per year)				
Study	**40**	**110-120**	**250**	**380**	**630**
	Marginal Costs C$/tonne-sequestered				
Moulton/ Richards (1990)	n.a.	26	33	38	55
Adams et al. (1993)	n.a.	30	40	60	150
Parks/Hardie (1994)	17	135	n.a.	n.a.	n.a.

Source: Sedjo, Roger A., et al, *Managing Carbon Via Forestry: Assessment of Some Economic Studies, Discussion Paper* - Resources for the Future.

It should be noted that the substantially higher costs found in the Parks and Hardie study can be partially explained by their use of: (i) lower forest growth rates; (ii) higher opportunity costs of alternative land uses; and (iii) different period of capitalization over which the plantation costs are distributed.

14.4.2 Agroforesty

Agroforesty involves the deliberate retention or introduction of a mixture of trees or other woody perennials into crop/annual production fields. Agroforestry practices for C pools may involve the

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[159] Ibid, pg. 11.

establishment of fuelwood and fibre plantations, intercropping systems (trees, agronomic and horticultural crops) and shelterbelts and windbreaks.[160]

The capacity for land to be converted from agricultural to non-agricultural uses depends on the extent to which agricultural land is not required for the production of food crops. It has been suggested that in regions with current food surpluses such as the U.S., Canada, and western Europe, the agricultural land base can be reduced. However, some consider the available options for expanding forest areas in the temperate and northern latitudes to be constrained, if more extensive farming systems are introduced.[161]

14.4.3 Forest Protection

Slowing forest loss through protection (e.g., the rainforest) offers an opportunity to reduce anthropogenic GHG emissions. This management practice may involve purchasing land which is threatened to be cut down by logging interests. Since protection of threatened forests results in many environmental, economic, and social benefits outside of carbon sequestration, forest protection may offer one of the most socially cost-effective mitigation technologies. Despite this, forest protection is viewed negatively by some interest groups and developing countries. These groups argue that some forests that are protected may not have been threatened and therefore there are no real sequestration benefits as these benefits would have occurred anyway.[162]

14.4.4 Management of Logging Residues and By-Products

Logging residues and timber processing by-products (including bark, sawdust and chips) are currently being utilized as bioenergy in many countries. This impacts the amount of fossil-fuel (oil and gas) based energy that needs to be produced. In addition, whole tree harvesting of energy from biomass (where branches, needles, roots and stumps are removed) can also increase the amount of the forest available for bioenergy by allowing the remaining trees to grow at a faster rate.[163]

14.4.5 Protection Against Fire

From a carbon storage viewpoint, fires are classified into: non-stand replacing and stand replacing fires. Non-stand replacing fires often occur in uneven age forest and usually produce low immediate carbon releases. Stand replacing fires are dramatic events causing a complete mortality of the over story. The effects of these fires are that: (i) C is redistributed amongst the

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[160] Ibid, pg. 43.

[161] Ibid, pg. 44.

[162] Trexler, Mark., Considerations in Forecasting the Demand for Carbon Sequestration and Biotic Storage Technologies, pg. 6.

[163] Organization for Economic Cooperation and Development, Policies and Measures for Common Action - Working Paper 7 - Agriculture and Forestry, Identification of Options for Net GHG Reduction, pg. 40.

various ecosystem pools and subsequent post-fire releases may be as much as three times the immediate releases; (ii) C is released into the atmosphere as CO_2 and other C compounds including CO and CH_4; and (iii) the forest structure is reset and succession is started.

Eliminating these large C releases is an attractive option and has been advocated in one GHG mitigation strategy in Russia. However from a forest management viewpoint, suppression of fires may merely open the way for other pathological agents which would normally have been kept at bay by the periodic cleansing action of wildfires. Some experts have suggested that if it is difficult to protect forests against fires, reliance on forests for C mitigation may not be wise, even on a temporary basis.[164]

14.4.6 Protection Against Disease, Pests and Other Herbivores

Aerial applications of chemical or biological pesticides are generally not effective in eliminating insect populations. The use of these chemicals may also have substantial impacts on biodiversity. In addition, the endemic impacts of insect disease and herbivores may reduce the net increment of forest phytomass. The effect on C sequestration is not clear and depends on many factors including forest age, disturbance type and regrowth.[165]

14.4.7 Salvage of Dead and Dying Trees

Removal of decomposing C from the natural system may enable an increase in the net C storage associated with a given piece of land. The actual carbon sequestration will depend on three factors: (i) whether more C is then transferred to forest products than would be the case if the C is left on site; (ii) the extent to which site regrowth is increased; and (iii) how much fossil fuel is used in the salvage and product manufacture and distribution options.[166]

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[164] Ibid, pg. 41.

[165] Ibid, pg. 42.

[166] Ibid.

14.4.8 Biomass Energy

This management practice refers to the use of biomass as a raw material or as a direct source of energy, therefore displacing fossil fuel based energy sources. The two major opportunities to reduce carbon emissions by substituting wood for other materials are:

- direct wood replacement of fossil fuels used as energy sources; and
- the substitution of wood products, such as lumber and plywood, for materials, such as steel, concrete and plastics that require much larger amounts of energy to convert into forms suitable for use in construction, manufacturing and shipping. Estimates suggest the energy required for using steel and concrete per unit of residential construction is about eight times that required for softwood timber substitutes.[167]

Currently, biomass supplies about 7% of Canada's energy needs. However, there is potential for a greater contribution to reducing fossil fuel based CO_2 emissions. For instance, estimates suggest that biomass energy may be able to displace 0.5-3.8 Pg C/yr of fossil fuel emissions in a doubled CO_2 world.

Increased recycling of wood fibre and wood products is another opportunity for lowering carbon emissions. Much less energy is required to convert recycled products into forms suitable for further use than is needed to grow, harvest, and process timber cut from forests. The increase in useful life also reduces the rate of carbon emissions that take place when wood products and fibres are no longer in use and are burned or decay. In addition, recycling reduces the volume of timber needed from forests and increases storage life of carbon in standing trees. It has been shown that with high rates of recycling, carbon emissions in the U.S. could be reduced by as much as 28 million tons annually by 2010 and that carbon storage in forests could be increased by 13 million tons in 2010.[168]

When forest or agricultural lands are used to produce fuels, atmospheric carbon is reduced by: (i) the amount of net increase in carbon sequestered in woody crops; plus (ii) reductions in net carbon emissions due to the extent that the renewable energy crop replaces fossil fuel use. This forest management option is thought to be quite promising with some analysts concluding that forest land could contribute substantially to global carbon stabilization through sustained production of fuel for biomass to replace fossil fuel as an energy source.

Work undertaken in the developing world has estimated the carbon savings and costs of biomass energy projects assuming alternative types of technologies including advanced energy conservation processes. Results suggest that the cost per ton of carbon saved through these

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[167] American Forests, Forests and Global Change -Volume 2 Forest Management Opportunities For Mitigating Carbon Emissions, pg. 250.

[168] Ibid, pg. 251.

biomass energy projects runs from \$7 to \$65 per ton.[169] However, experts in the field have suggested that before biomass can become cost competitive with fossil fuels, substantial improvements are needed in biomass feedstock yield and in the efficiency of conversion.

An alternative approach involves co-firing (e.g., the use of at least two different fuels at the same time under controlled combustion conditions). This practice is common in the Great Lakes region in the paper industry where significant volumes of bark and related waste are generated on site. Even where mills purchase various forms of biomass, the cost per ton is substantially less (often about 50% than the cost of coal). Recent research has estimated that the cost per ton of reducing carbon emission runs from a negative cost to \$145, depending on the technology and the activity.[170]

14.4.9 Urban Forestry

Expansion and better management of urban forests has been proposed as one way to combat climate change. This management practice can also be viewed as a demand side management practice for energy conservation. Urban trees directly affect carbon dioxide emissions through two avenues: (i) by directly sequestering carbon in the trees and in the urban soils; and (ii) by reducing energy requirements for cooling and heating homes and buildings.

The energy conservation effects of a single tree have been estimated to prevent the release of 15 times more atmospheric carbon that the amount of carbon that the tree can sequester. Three properly placed trees around homes and small buildings can cut air conditioning demand by as much as 44%. In addition, windbreaks can save about 15% of the heat energy used as well as reduce winter heating costs by 4 to 22 percent.[171]

Work conducted in this area has determined that investments in urban trees substantially reduce energy requirements while the economic returns are quite significant. Experts in this field have suggested that one of the greatest research needs is in determining the economics of tree planting in urban areas for the purpose of carbon sequestration, and for the purposes of reducing energy requirements (thus reducing CO_2 from power generation from fossil-fuels).

Research to date has indicated that the marginal cost of modifying urban tree planting to enhance energy conservation is significantly lower than the marginal benefits in energy savings, carbon sequestered, and CO_2 emissions avoided.[172]

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[169] Ibid, pg. 24.

[170] Ibid, pg. 25.

[171] Sampson, Neil, Sedjo, Roger A., Wisniewski, Joe, Economics of Carbon Sequestration in Forestry: An Overview, pg. 23.

[172] Ibid, pg. 27.

14.4.10 Forest Management

By undertaking forest management practices, the volume of biomass is increased, therefore increasing the carbon sequestration potential of these forests. Among the forest management practices that have been suggested are: increasing productivity of poorly stocked timberlands; thinning overstocked stands where growth is being impeded; harvesting and regenerating overmature timber; delaying harvest of other stands; and using conservation easements to modify management and harvesting practices.

The potential for carbon sequestration from these practices can be significant. For instance, the U.S. Office of Technology Assessment estimated that 30-40% of U.S. timberlands could be brought under more intensive management, increasing carbon sequestration by tens of millions of tons per year.[173]

Carbon Sequestration from Forest Management Activities

	Increasing the Productivity of Poorly Stocked Timberland[1]			Intermediate Stand Treatment for Overstocked Forests[2]		
	Years	**Ft^3/acre/yr**	**Lb/acre/yr**	**Years**	**Ft^3/acre/yr**	**Lb/acre/yr**
Region and Forest Type	Cutting Period	Growing-Stock Volume	Carbon Sequestered	Cutting Period	Growing-Stock Volume	Carbon Sequestered
Northern U.S.						
Oak-hickory	65	24.4	568	65	8.3	355
Maple-beech-birch	65	21.3	148	65	8.3	328
Aspen-birch	65	13.1	14			
White/red/jack pine	65	9.2	182	65	8.3	251
Spruce-fir	65	3.6	-322			
Bottomland hardwood	65	4.7	152	65	8.3	323
Nonstocked	65	16.3	437			
Pacific Coast						
Douglas-fir	80	55.8	790	80	10.8	275
Ponderosa pine	80	11.9	-34	80	10.8	242
Hardwoods	80	89.3	1,814			
Nonstocked	80	111.0	2,680			

Source: American Forests, *Forests and Global Change, Volume I - Opportunities for Increasing Forest Cover*

[1] includes regeneration and stand conversion to a different forest type.

[2] includes pre-commercial thinning, commercial thinning and other stocking control.

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[173] Trexler, Mark., Considerations in Forecasting the Demand for Carbon Sequestration and Biotic Storage Technologies, pg. 6.

It should be noted that forest management approaches can pose a number of challenges. For instance, carbon sequestration is often just one of several objectives being pursued through forest management, and often not the most important one to project developers. In addition, carbon sequestration and economic management objectives do not always overlap. For example, forest management practices are often used to replace non-commercial species with commercial species on an "under-productive" stand. While economically worthwhile, there may be no associated carbon benefit. It has also been suggested that the CO_2 benefits associated with forest management projects can be very difficult to monitor and verify.[174]

Compared to tree-planting (e.g., reforestation, afforestation, etc.), very little work has been undertaken to estimate the costs of sequestering carbon through the use of various forest management practices. Generally the literature has shown that forest management techniques are not as viable (from a carbon sequestration standpoint) than other options such as tree planting and forest protection. It has been suggested that the least promising forest management practices, from a direct carbon storage point of view, are those such as thinning, fertilization and other stand improvement treatments.

One of the few attempts at deriving cost estimates are through studies by Hoen and Solberg based on forests in Norway. The results of these studies have suggested a relatively high cost per ton of carbon sequestered for most forest management practices (e.g., thinning). For example, these studies have concluded that forest fertilization generate relatively high marginal costs of about $103 per incremental ton of carbon captured for a Norwegian forest.[175]

However it should also be remembered that forest management techniques that allow larger sections of the forest to be harvested and converted to long-lived wood products may sequester a greater volume of carbon in the long term in both the forest itself and in the forest product stock. As an example, while thinning for pulpwood may not increase the total volume on the stand, it may generate a greater amount of sequestered carbon in the long run if it allows more forest stands to produce solid wood products.

14.4.11 Reduced Impact Logging

Damage to forests during harvesting can be reduced by as much as 50 percent in some regions of the world by taking basic steps such as removing vines before cutting, directional tree felling, and better planned extraction on properly constructed and utilized skid trails. In addition to the carbon sequestration benefits that are realized, reduced impact logging can have ancillary benefits such as promoting sustainable forestry practices and preserving biodiversity, reducing soil erosion, and protecting water quality.[176]

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[174] Ibid.

[175] Ibid, pg. 16.

[176] Ibid, pg. 7.

Reduced impact logging is expected to reduce releases of carbon associated with harvests. A study by Putz and Pinard (1993), estimated that modest modifications in harvesting techniques in the selectively logged forests of Sabah could result in 46 more tons of carbon per hectare after 15 years at a cost of only about $4.26/ton. However it should be noted that the applicability of this study to North America is questionable because the typical tropical forest harvest regime involves selective logging while most temperate forest harvesting involves clear cutting.[177]

14.5 R&D Capabilities and Requirements

The Canadian Forestry Service (CFS) is the organization that has conducted the most research in the area of carbon sequestration in Canada. In addition, work is being expanded at the CFS due to the results of the Kyoto Protocol.

Canadian Forestry Service - Science and Technology Networks

Technology Network	Location
CFS - Headquarters	Ottawa, ON
CFS - Atlantic Forestry Centre	Fredericton, NB
CFS - Laurentian Forestry Centre	Sainte-Foy, PQ
CFS - Great Lakes Forestry Centre	Sault Ste. Marie, ON
CFS - Northern Forestry Centre	Edmonton, AB
CFS - Pacific Forestry Centre	Victoria, BC

The Northern Forestry Centre in Edmonton (Mr. Mike Apps) has been designated as the lead R&D centre in Canada for work in the area of climate change and carbon sequestration in forests. The Atlantic Forestry Centre (Mr. Mike Levine) and the Laurentian Forestry Centre (Mr. Pierre Bernier) are also undertaking some R&D with respect to carbon cycling and carbon sequestration, however not to the extent that the Northern Forestry Service is.

The three major university forestry programs in Canada are also involved in biomass sequestration, namely the University of Toronto, the University of New Brunswick (Mr. Paul Arp) and the University of British Columbia (Mr. Andy Black).

In the private sector, the Canadian Pulp and Paper Association (CPPA) is involved in this area. ESSA Technologies (Mr. Werner Kurz), a consulting firm on the west coast has been active with the Northern Forestry Service in their work on the carbon budget of Canadian forests.

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[177] Ibid, pg. 17.

Specifically, the CFS and ESSA Technologies have developed a comprehensive model of the carbon budget of Canadian forests and the Canadian forest products sector. This model, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), is a national-scale model integrating forest biomass, soil and forest products sector C dynamics. The model has been used extensively to determine the net C budget of Canadian forests under different forestry practice scenarios.[178]

The CBM-CFS was developed to enable policy makers to analyze the effects of climate change and various forest management/land use practices on the C budget of the Canadian forest sector. The CBM-CFS is based on recent forest and soils inventory data, other government and industry statistics for timber harvesting, utilization and decay of forest products and losses from fires and insect attack.[179]

The CBM-CFS incorporates five important design criteria, namely:[180]

1. all major systems components are analyzed;
2. below-ground biomass C dynamics are simulated;
3. soil dynamics are directly linked to biomass dynamics;
4. disturbance regimes and their effects on C pools are simulated; and
5. age-class structures are explicitly recognized.

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[178] Kurz, W.A., and Apps, M.J., An Analysis of Future Carbon Budgets of Canadian Boreal Forests, 1995, in Water, Air and Soil Pollution, pg. 322.

[179] Apps, M.J. et al., Estimating Carbon Budgets of Canadian Forest Ecosystems Using a National Scale Model, pg. 245.

[180] Kurz, W.A., and Apps, M.J., Contribution of Northern Forests to the Global C Cycle: Canada as a Case Study, in Water, Air, and Soil Pollution, 1993, pg. 171

Change in Ecosystem C of Canadian Boreal Forest Over 1990-2040

Scenario	Assumptions	Area Planted (Mha)	Change in Ecosystem C (Pg C)
Base Run	• harvest and planting at 90% of 1985-89 levels. • fire at 60% of 1985-89 levels. • insect-induced mortality at 100% of 1985-89 levels.	4.6	0.86
Low Fire	• fire at 50% of Base Run.	4.6	2.3
High Fire	• fire at 200% of Base Run.	4.6	-1.4
Plant All	• all disturbed areas are planted.	132.0	1.8
Conversion	• non-stocked areas are converted to high yield stands at 1% of eligible area each year.	58.2	0.92
Selective Conversion	• non-stocked area with less than 2 Mg C ha converted to high yield stands at 5% of eligible area each year.	51.8	9.2

Source: Kurz, W.A., and Apps, M.J., *An Analysis of Future Carbon Budgets of Canadian Boreal Forests*, 1995, in Water, Air and Soil Pollution, pg. 324 &327

The CFS has used the CBM-CFS to undertake several studies on the future carbon budget of Canadian forests under different land and forest management scenarios. For instance, one paper discusses the future (1990-2040) carbon budgets of the Canadian boreal forest, under different assumptions about natural disturbances, rates of reforestation of distributed land and conversion of non-stocked land to productive forest stands.

The fifth and sixth scenarios above determine the impacts on the C budget of converting areas currently considered non-stocked to stocked stands with high growth rates (this is a best case scenario). Non-stocked stands do not meet stocking standards but may contain some forests.

The results of this study indicate that over the 1990-2040 time period, the Canadian boreal forest can range from a 1.4 Pg C source to a 9.2 Pg C sink. The most attractive option (in terms of sequestering C) is to aggressively plant trees in non-stocked areas at a rate of 5% a year. It should be noted that the results outlined above are for the entire 1990-2040 time period and are not annual changes.

The authors of the study indicated that the actual net uptake of atmosphere C is likely to be smaller than the results outlined above because:[181]

- this analysis does not account for the additional release of fossil C require to implement some scenarios;
- this analysis assumes 100% success in all planting and site conversion projects; and
- the economic factors responsible for low initial stocking levels in some areas may also reduce the high growth rates assumed after conversion of these areas to stock stands.

Several Canadian companies, primarily located on the west coast specialize in forestry practices (e.g., reforestation, forest management, forest protection, etc.) and will be crucial to the implementation of any biomass sequestration measure that is implemented in Canada.

Canadian Capabilities in Forest Management

Company	Location	Expertise
Bowell Consultants Ltd.	Vancouver, BC	forestry, reforestation, energy conservation
Brinkman & Associates Reforestation Ltd.	New Westminster, BC	integrated silviculture services
Conifer Enterprises	Nanaimo, BC	forestry, reforestation
Dendron Resource Surveys Ltd.	Ottawa, ON	forestry, reforestation
FOR International Ltee.	Montreal, PQ	forestry, reforestation
Forest Lease Inc.	Spruce Grove, AB	forestry, reforestation
KBM Forestry Consultants Inc.	Thunder Bay, ON	forestry, reforestation
Longwood Forestry Service Ltd.	Trout Creek, ON	forestry, reforestation
Pacific Regeneration Technologies Inc.	Victoria, BC	forest seedling production
Reid Collins Nurseries Ltd.	Albergrove, BC	reforestation, forest rehabilitation
Sandwell Inc.	Vancouver, BC	forestry, reforestation, energy conservation
Spencer-Lemaire Industries Ltd.	Edmonton, AB	reforestation
Sylva Management Services Ltd.	Kamloops, BC	reforestation
Sylvico Inc.	Longueuil, PQ	forestry, reforestation, forest management, forest protection
Woodlot Service (1978) Ltd.	Fredericton, NB	forestry, reforestation

Source: Woodbridge & Associates, An Industry Canada Action Plan: Canadian Environmental Industries and Climate Change Business Opportunities, 1994.

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[181] Kurz, W.A., and Apps, M.J., An Analysis of Future Carbon Budgets of Canadian Boreal Forests, 1995, in Water, Air and Soil Pollution, pg. 328.

14.6 Recommendations

The potential for forest management practices to sequester carbon is quite significant. Work to date has determined that many available practices are proven and cost effective. Given the large land mass in Canada, the significant amount of land that is available to be used for reforestation as well as the various preservation practices that can be employed, Environment Canada (in conjunction with the CFS) would be well suited to undertake additional research on where the greatest potential lies, both in terms of actual forest management practices to employ as well as the geographic location to concentrate this activity.

The Kyoto Protocol has determined that emissions are to be calculated on a gross-net approach. Therefore, for the baseline (1990 for main GHG gases and potentially 1995 for the trace gases), sinks are not be included in the total. However for the target date of 2008-2012, a net approach (i.e., sinks can be applied) is to be used. Many countries did not want sinks to be available to offset GHG emissions. Therefore, Canada is in a very favourable position because of its unique geographic and land use characteristics to offset a significant portion of their GHG emissions through cost-effective forest management practices.

Canada's Forest Plan has recognized the potential for carbon sequestration by announcing an objective to plant 325 million trees in rural and city areas as well as conduct research to assess forest sinks and their possible role in offsetting GHG emissions. Canada's National Action Plan on Climate Change has mentioned several approaches to sink enhancement and emission mitigation but none are being implemented in the forestry sector apart from fire and pest control management measures.

15. Underground Storage in Reservoirs (Enhanced Oil Recovery)

15.1 Summary

Carbon dioxide can be stored underground in rock structures and aquifers. This disposition method represents a reservoir (as opposed to a sink) for carbon dioxide which remains in the ground, under pressure, thousands of feet below the surface. This analysis focuses on a practical application of this option: the use CO_2 for enhanced oil recovery (EOR) at partially depleted oil reservoirs in Western Canada. From this application, technology development and cost implications for broader application of underground storage can be inferred.

EOR represents a reduction option for large point sources of carbon dioxide emissions such as ammonia plants, electrical power facilities, ethylene petrochemical plants and other sources where the CO_2 can be readily captured for treatment, extraction and inexpensively transported via pipeline to an underground storage reservoir.

Net Cost Summary of CO_2 for Underground Storage

Reduction Potential	**First 10 to 15% of Total Western Canada (largest sources)**	**Next 15 to 60% of Total Western Canada (smaller sources)**
	($/T Net* CO_2)	($/T Net* CO_2)
Total costs (annualized capital, operating & transportation)	93 to 115	115 to 235+
Crude oil revenue available	(~90)	0
Net cost at current crude oil price	~3 to 25	~115 to 235+

Range of annualized costs reflects weighted average of annual operating costs for large and small facilities, as provided below.

* Net CO_2 takes into account emissions resulting from capture, treatment, extraction and transportation processes (assumed 65% of gross CO_2 captured).

The total direct capital cost associated with capturing, treating, extracting and transporting approximately 50 kilotonnes per day of CO_2 to nearby oil reservoirs for enhanced recovery in Western Canada is estimated at $4 to $6 billion. This level of investment could deal with all the emissions from ammonia and petrochemical facilities in Alberta and Saskatchewan, as well as a portion of the CO_2 emissions from major utilities, and other large point sources. However, while a portion of the CO_2 used for EOR would result in increased hydrocarbon (oil or gas) production, increased emission reduction levels (i.e., using increased amounts of CO_2) would have reduced associated enhanced oil production benefits. With negligible or no benefits of oil production, direct unit costs increase with decreasing quantities of CO_2 handled. These can range from 115 to 235 C\$/T-Net CO_2 reduced, or more.

Only one commercial carbon dioxide EOR project is operating in Canada. Numac Energy uses 0.2 kilotonne per day of CO_2 purchased from an ethylene plant to recover oil from a field near Joffre, Alberta. More EOR projects are anticipated. In 1997, PanCanadian Petroleum, of Calgary, AB and 36 partners announced a project to use carbon dioxide to enhance crude oil production from the Weyburn oil fields in Saskatchewan. In 1998, Dakota Gasification plans to start construction of a $140 million pipeline to transport carbon dioxide from Beulah, ND to Weyburn, SK, a distance of close to 325 kilometers. The source of the carbon dioxide is the Great Plains synfuel plant at Beulah, ND. Carbon dioxide gas consumption for this project is expected to average 5.5 kilotonnes per day, or nearly 2,000 kT per year. Over the life of the project a total of 30,000 kT of carbon dioxide will have been stored. The result will be an increase in oil production from the field from 18,000 barrels to 30,000 barrels per day by 2008.

15.2 Reduction Technology

Carbon dioxide flooding is one of a series of technology options that can be applied to enhance oil recovery from reservoirs. Carbon dioxide acts as a solvent of the hydrocarbon mixture that constitutes crude oil. Pumping carbon dioxide into the reservoir allows the oil to flow to the surface. Hydrocarbon gases and the carbon dioxide (along with water) flow to the surface where they are separated. The carbon dioxide is reinjected, to minimize consumption and to maintain the reservoir pressure.

Carbon dioxide mixed with other gases may not be suitable for tertiary oil recover. Streams contaminated with significant amounts of acid gases (e.g., NO_x, H_2S, SO_2), water, and oxygen should be treated before use in oil recovery. Carbon dioxide content between 60 and 95% is preferred.[182]

Oil recovery from wells is typically classified in three categories. Primary recovery is the process of natural oil flow or merely pumping of the oil to the surface. Secondary recovery include use of water to maintain the reservoir pressure. Tertiary recovery methods include in-situ combustion (fire flood - rarely used), steam injection, carbon dioxide injection, injection of natural gas

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[182] Saskatchewan Research Council, S. Hueng, personal conversation, Feb. 4, 1998.

liquids (i.e., ethane, propane) and polymer or chemicals injection. Other ways to augment oil production or lower costs, include horizontal drilling, and various stimulation techniques.

15.2.1 Application of the Technology

Carbon dioxide reservoir flooding has been applied more in the United States than in Canada. In the early 1990s, approximately 125 kilotonnes/day of carbon dioxide was being used in the United States for enhanced oil recovery. Canadian use of carbon dioxide is presently less than 0.5% of that quantity. There are several reasons why carbon dioxide floods are more popular in the United States. One factor is that the oil reservoirs in the southern United States are older. A more important factor is the availability of low cost carbon dioxide to U.S. oil producers. Contributing to better availability of carbon dioxide is the higher content in U.S. wells. Generally, Canadian wells contain less carbon dioxide, than wells in such states as Montana and Wyoming. Close proximity of carbon dioxide sources and older oil wells along with an existing carbon dioxide pipeline infrastructure facilitate the economic use of carbon dioxide for tertiary recovery. By comparison, in western Canada the sources of available carbon dioxide are generally not of the quality (CO_2 purity) and quantity that can be used for tertiary oil recovery. In addition, pipeline infrastructure that facilitates economic delivery between sources and users does not exist. Still another factor is the greater adoption of alternative production methods (i.e., horizontal drilling) to increase oil production in Canada.

Approximately 70 oil fields in the southern and western United States employ carbon dioxide for tertiary oil recovery. In Canada only three sites have been identified as using this recovery process. However, greater application of the technology is expected in the future.

Oil Fields in Canada on Carbon Dioxide Flood

Oil field	Location	Companies Involved	Status
Midale	Saskatchewan	Shell Canada Ltd.	Pilot
Joffre	Alberta	Numac Energy Inc.	Ongoing
Harmatton	Alberta	Shell, Mobil	Abandoned CO_2
Weyburn	Saskatchewan	PanCanadian, others	Awaiting approvals

Numac Energy is presently using CO_2 for enhanced oil recovery. The company purchases CO_2 from Novacor's ethylene petrochemical operations at Joffre, AB. Novacor generates carbon dioxide from ethane treatment facilities and from its ethylene plant. This CO_2 is treated, compressed and pipelined to Numac's oil field operations less than half a mile away. Numac took over the Joffre field after Imperial Oil abandoned operations, having depleted the readily available reserves which constituted 30 to 40% of the total. (approximately 60 to 70% of the oil remains in the ground). Numac has been able to increase production from the field from zero to

600 barrels per day by using a total of 0.2 kilotonnes per day of carbon dioxide. Numac plans to increase its requirements for carbon dioxide as new portions of the field are opened.

In 1997, PanCanadian Petroleum, of Calgary, AB and 36 partners announced a project to use carbon dioxide to enhance crude oil production from the Weyburn oil fields in Saskatchewan. In 1998, Dakota Gasification plans to start construction of a $140 million pipeline to transport carbon dioxide from Beulah, ND to Weyburn, SK, a distance of close to 325 kilometers. The source of the carbon dioxide is the Great Plains synfuel plant at Beulah, ND. PanCanadian and its partners have negotiated a 15 year contract for the supply of carbon dioxide, which should begin to flow by late 1999. The project is awaiting approvals from Provincial authorities.

Carbon dioxide gas consumption for this project is expected to average 95 million cubic feet per day, (5,500 tonnes per day) or nearly 2,000 kT per year. Over the life of the project a total of 30,000 kT of carbon dioxide will have been stored. The result will be an increase in oil production from the field from 18,000 barrels to 30,000 barrels per day by the year 2008. The Weyburn oil field is a large field which began production in the mid-1950s. Original estimated reserves were 1.2 billion barrels.

The quantity of carbon dioxide available from various sources must be high enough to justify economic utilization. The costs of carbon dioxide stream purification, pipeline transportation and injection must be amortized over a large quantity of recovered oil which requires a large quantity of carbon dioxide.

Enhanced oil recovery with carbon dioxide is not applicable to all oil fields in Western Canada. A comprehensive study initiated by representatives of the energy industry and Alberta Oil Sands Technology and Research Authority (AOSTRA)[183] identified six fields which were best suited to EOR with carbon dioxide based on some of the following factors:

- required porosity to provide space for fluids;
- permeability to allow fluid flow and a seal unpermeable over geological time;
- pool size;
- oil density; and
- minimum miscibility pressure and oil production history.

The following six fields were selected:

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[183] Bailey, R.T., McDonald, M.M., Alberta Oil Sands Technology and Research Authority, Trans Alta Utilities Corp., "CO_2 Capture and Use for EOP in Western Canada, 1. General Overview", 1995?, Calgary, AB.

Reservoir	Location	Operator (early 1990s)	Formation	Production	Original Oil in Place (million m^3)
Carson Creek North	Central Alberta	Mobil	Devonian Reef	Light oil miscible	58
Pembina	Central Alberta	Mobil Amoco Imperial Oil	Cretaceous Sandstone Conglomerate	Light oil miscible	250
Redwater	Central Alberta	Imperial Oil	Devonian D-3	Light oil miscible	168
Elswick	S/E Saskatchewan	Westcoast	Mississipian Carbonate	Light oil miscible	4
Aberfeldy	West Central Saskatchewan	Husky		Heavy Oil immiscible	94
Carson Creek Gas	Central Alberta	Mobil	Devonian Reef	Gas	

The reservoirs identified had the capability to utilize close to 50 kilotonnes per day of carbon dioxide. This quantity represented 12% of Alberta's and Saskatchewan's total carbon dioxide emissions. It also represented for approximately 50% of Alberta's emissions from either the electrical power industry or oil and gas industry[184].

15.2.2 Capture, Treatment and Extraction

The AOSTRA study also concluded that it was technically feasible using commercially available equipment to capture, treat and extract large quantities of carbon dioxide from sources such as power plants, industrial furnaces (including ethylene furnaces) and other sources.

One component of the study[185] examined capture, treatment and extraction of carbon dioxide from hot flue gas streams. The results of the study are briefly described for different facilities. (Reference conditions for the case studies may have changed since the study was conducted).

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[184] Ibid

[185] Vandenhengel, W., Miyagishima, W., "CO_2 Capture and Use for EOP in Western Canada, 2. CO_2 Extraction Facilities", 1995, SNC Lavalin., Calgary, AB.

Target Quality of Carbon Dioxide

Component	Composition
CO_2	95% min.
$N_2 + CH_4 + H_2$	4% min.
Hydrogen sulphide (H_2S)	20 ppm min.
SO_2	300 ppm min.
NO_x	100 ppm min.
O_2	100 ppm max.
CO	3 kPa max.

Source: Industry sources

A power station located in southern Saskatchewan burns coal with ~0.6 wt% sulphur. A two stage flue gas conditioning process was selected. This consisted of water washing followed by scrubbing (Anderson 2000) using sodium sulphite as the active ingredient to reduce SO_2 levels by over 98%, to less than 5 ppm. Carbon dioxide extraction with chemical absorption using mono-ethanolamine (MEA) was recommended. Inhibitors to prevent oxidation and corrosion need to be incorporated with the MEA. Water removal from CO_2 is accomplished during compression interstage cooling and knock-out, as well as a in a conventional tri-ethylene glycol (TEG) dehydration system. Suppliers of the MEA carbon dioxide extraction technology include Union Carbon, Fluor Daniel (Dow).

At another power plant which used coal with a lesser amount of contained sulphur (~0.2 wt%), a magnesium enhanced lime scrubbing process (Dravo) is recommended versus sodium sulphite scrubbing. Other available systems for removal of SO_2 include use of activated coke adsorption and Cansolv wet solvent scrubbing.

The system appropriate for an ethylene facility using natural gas and fuel gas (generated internally) with very low levels of sulphur included water wash cooling followed by inhibited MEA absorption. The CO_2 is dehydrated using compressor interstage cooling and knock-out with final TEG dehydration system.

The Saskferco Products Inc. ammonia plant (formerly known as the Bi-Provincial Upgrader) in Belle Plaine, SK generated nearly 1,000 tonnes per day of CO_2 (may be different currently) in the early 1990s. The process chosen to remove the CO_2 was an MEA absorption system.

It should be noted that the capture, treatment, extraction (including regeneration of absorbing media) are energy intensive processes which consume energy and result in CO_2 emissions. Therefore the net reduction in emissions can range from 50 to 70% of the gross amount of CO_2 captured.

Costs of CO_2 Capture, Treatment & Extraction

Sources	Production	Capital Cost (current)	Annual Operating Cost	Total Annualized Cost
	(tonnes/day)	($ million)	($ million/yr)	($/T CO_2-Gross)
Boundary Dam Power Plant	8,034	800	95	68
Sundance Power Plant	6,750	600	75	63
Novacor ethylene plant (Joffre)	3,345	200	65	75
Novacor ethylene plant (small scale)	100	20	3	150
Saskferco Products (ammonia plant)	1,026	100	20	90
Hanlan Robb Sour Gas Plant (amine)	628	85	13	80

Source: AOSTRA

15.3 Costs and Benefits of Enhanced Oil Recovery

The total direct capital costs associated with capturing, treating, extracting and transporting approximately 50 kilotonnes per day of CO_2 to nearby oil reservoirs for enhanced recovery is estimated at $4 to $6 billion.

Net Cost Summary of CO_2 for Enhanced Oil Recovery

Cost component	Capital Costs	Overall Total Costs (Annualized Capital plus Operating#)
	($ billion)	($/T Net* CO_2)
Capture, treatment, extraction	4.0 - 5.0	90 to 110
Transportation to reservoirs	0.6 - 0.8	3 to 5
Total	4.6 - 5.8	93 to 115
Daily and Unit Cost Summary	($ million/day)	($/T-Net CO_2)
Annualized capital and operating	$3 to $4	93 to 115
Crude oil revenue	($~2.8)	(~90)
Net cost at current crude oil price	$0.2 to 1.2	(~3 to 25 $/T-Net CO_2)

Range of annualized costs reflects weighted average of annual operating costs for large and small facilities, as provided below.

* Net CO_2 takes into account emissions resulting from capture, treatment, extraction and transportation processes (assumed 65% of gross CO_2 captured).

The study conducted by AOSTRA developed a realistic scenario of using approximately 50 kilotonnes per day of carbon dioxide collected from major sources, and using this to enhance oil recovery. Although this amount would actually be applied to the oil fields, the net amount of CO_2 reduction would be less than this quantity due to emission penalties associated energy requirements for capture, treatment, extraction and transportation. It has been assumed for this study that the net CO_2 emissions reduction is 65% of gross CO_2 (50 kilotonnes per day), or 32.5 kilotonnes per day.

The estimated additional amount of oil that could be recovered with this quantity of carbon dioxide was 20,000 m^3 (126,000 barrels per day). This amount of oil at current prices (~22 C$/barrel) has a value of $2.8 million per day. The economics of using carbon dioxide for EOR are sensitive to the price of crude oil. During periods of high crude prices, the economics for carbon dioxide use can provide net benefits to producers.

In western Canada the required infrastructure required to facilitate the use of the carbon dioxide for tertiary oil recovery does not exist. However, in Saskatchewan, the beginning of a pipeline infrastructure may be in place before the year 2000. New infrastructure would be required in Alberta where the long term potential for this technology to provide a reservoir for carbon dioxide is greater.

15.3.1.1 Case Studies: Weyburn Field in Saskatchewan

The proposed project in Saskatchewan for the Weyburn field provides a useful case study of costs and benefits associated with enhanced oil recovery using carbon dioxide. The costs point to a net benefit resulting from this project. However, it should be kept in mind that there is a wide range of costs and benefits for each carbon dioxide source/reservoir combinations available in Western Canada. The economics for each source/reservoir will be unique and strongly influenced by the characteristics of each oil field. It should also be kept in mind that there will be diminishing returns over time and many fields that would be only marginally enhanced with carbon dioxide recovery. Therefore the economics of using carbon dioxide are better for new fields in which the technology is applied. Costs will be higher as carbon dioxide utilized is increased.

PanCandian's reported total cost of the Weyburn project is approximately C$1.1 billion over the lifetime of the project. Dividing this total cumulative cost (at current dollars) over the total carbon dioxide placed in the reservoir over 15 years results in an average cost of 36 C$/T Gross CO_2 (or 55 $/T Net CO_2, or ~10 C$ per barrel of oil produced). Major cost components include:

- construction of 325 km pipeline from Beulah, ND to Weyburn, SK (~C$140 million);
- treatment and compression for the gas;
- facilities to treat oil and carbon dioxide for reinjection; and
- debt and return on capital invested.

These cost components will be incorporated in the price of the carbon dioxide that PanCanadian and others will pay. Dakota Gasification will be responsible for construction of the pipeline and carbon dioxide delivery under high pressure.

The economic benefits for this project are substantially greater than the direct costs. Total increased production over the life of the project is estimated at 122 million barrels of oil. At current world oil prices (~22 C$/barrel), the total value of this increased production is approximately C$2.6 billion. Costs to pump, process and transport the oil to refineries would reduce the netback for producers. However, these costs would not come close offsetting the substantial economic gains offered by this project.

In summary, the net gain of using carbon dioxide for enhanced oil recovery is very approximately estimated at 40 to 60 $/tonne of CO_2 (or 11-17 $/barrel of oil). If the carbon dioxide was merely stored underground without oil recovery the cost would be on the order of 36 C$/tonne, or more.

These approximations of the economics of carbon dioxide use for enhanced oil recovery are similar to those experienced by Numac Energy for their field at Joffre, AB.[186]. However the actual costs and benefits of associated with oil production can vary substantially depending on the field and the source of the carbon dioxide.

15.3.2 Emissions Reduction Potential

Capturing, treating, extracting and distributing carbon dioxide for enhanced oil recovery presents a long term opportunity to reduce emissions and increase the reserves of carbon dioxide underground in western Canadian oil and gas fields. The associated investment costs are in the billions of dollars. However, depending on crude oil prices, benefits from increased oil production may offset these costs.

The table below presents the major sources of carbon dioxide that could be evaluated for potential use in enhanced oil recovery. Some of the highest quantity point sources of carbon dioxide emissions in Alberta and Saskatchewan include: the utility plants using coal and other fossil fuels; oil and gas producers, processors and distributors; and various industrial facilities. Excluded from this list are residential, commercial, mobile and many other smaller sources of carbon dioxide.

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[186] John Flyn, V.P. Operations, Numac Energy, Personal conversation.

Major Carbon Dioxide Sources in Alberta and Saskatchewan

	Alberta	Saskatchewan	Total
		(Mt - CO_2)	
Power generation	47.9	13.4	61.3
Producers consumption	25.9	3.6	29.5
Industrial	17.2	4.4	21.6
Upstream oil and gas*	8.9	0.5	9.4
Other non-energy	9.0	0.6	9.6
Cement	0.9	0.0	0.9
Total major sources	109.8	22.5	132.3
Total provincial CO_2 emissions#	151.0	36.6	187.6

* excludes methane emissions that could be converted to carbon dioxide through oxidation
\# excludes other GHG emissions

Therefore, although the potential pool of carbon dioxide from major sources is large (roughly estimated at 132 Mt for 1995) and increasing in Western Canada, the conservative assumption is that only 10 to 15% (or ~50 kilotonnes per day) of this quantity would be used for enhanced oil recovery in situations where an economic benefit may be available. More carbon dioxide could be placed in non-producing underground reservoirs at higher costs and no direct oil or gas benefits.

15.4 R&D Capabilities and Requirements

Canadian research supporting the oil and gas sector is largely situated in Western Canada. In addition to oil and gas producers, the Alberta Research Council, Natural Resources Canada - CANMET, the Saskatchewan Research Council, the Alberta Oil Sands Research Technologies Authority, and universities located in the western provinces support the sector. There are also pockets of expertise in various institutions across Canada. Large oil producers such as Shell Canada, PanCanadian, and Mobil, as well as smaller producers such as Numac Energy have developed experience through pilot projects and field application of the technology.

Research areas identified by industry and research participants that are required to develop greater use of carbon dioxide for enhanced oil recovery include:

- purification of streams containing low carbon dioxide concentrations;
- reservoir characterization/screening studies;

- oil properties;
- geological analysis;
- pressure, volume, temperature (PVT) studies of CO_2 and oil mixtures;
- dynamic flow studies; and
- field operational parameter studies (pilot projects).

Alberta's and Saskatchewan's Departments of Energy have been involved in developing EOR technologies and communicating the potential benefits for its adoption. These are important stakeholders in this field which view carbon dioxide EOR as an important tool to allow Western Canada to meet reduction targets established at Kyoto.

15.5 Recommendations

Enhanced oil recovery presents a potentially important tool for large Western Canadian point sources emitters of CO_2. To further develop this technology and its application, numerous stakeholders need to work cooperatively to better understand technical issues, identify specific opportunities, define cost for different levels of CO_2 utilization, and assess economic risks associated with very large capital investments. Among the technology suppliers and other stakeholders which may need to become involved in this area are:

- research facilities;
- large CO_2 emission point sources - electric power facilities, ammonia plants, petrochemical ethylene plants, crude oil refiners etc.;
- governments (provincial, Natural Resources Canada, Environment Canada);
- pipeline companies; and
- oil and gas producers.

Although large CO_2 emission sources are more likely candidates for applying this technology, smaller and low cost niche sources/reservoirs match-ups may offer potential for near term development. Numac Energy is an example, of a match between a nearby source of CO_2 and a nearby, abandoned oil reservoir. Although the quantity of CO_2 is not large, the development of this application demonstrates a win-win for all stakeholders.

16. Summary of Costs and R&D Capabilties

16.1 Costs to Reduce GHG Emissions

The cost analysis for this study identifies key economic factors and provides an order-of-magnitude estimate for capital and operating expenditures associated with adoption of some of the technologies researched. Costs were not prepared for all 80 to 90 technologies identified and investigated. Therefore, cost totals are not representative of least or total industry or social costs to reduce GHG emissions.

Annualized Capital & Net Operating Costs to Achieve Reductions

(low cost scenarios)

	Capital	Operating	Total	Mt GHG Reduction	Reduction Levels	Capital	Operating	Total
		($ million)			(See Notes)		($/t-CO2)	
Non-energy	$338	$220	$558	29	26%(1)	$11.6	$7.5	$19.1
Underground storage (EOR)	$540	($515)	$26	9	7%(2)	$63.0	($60.0)	$3.0
Biomass carbon sequestration	$0	$67	$67	13	19%(3)	$0.0	$5.0	$5.0
Total				51	45%(4)			

1. 26% of total non-energy GHG emissions covered in this study.
2. 7% of major sources (energy and non-energy) in Western Canada
3. 19% of 67 Mt potentially achievable target.
4. 45% of total non-energy emissions covered in this study.

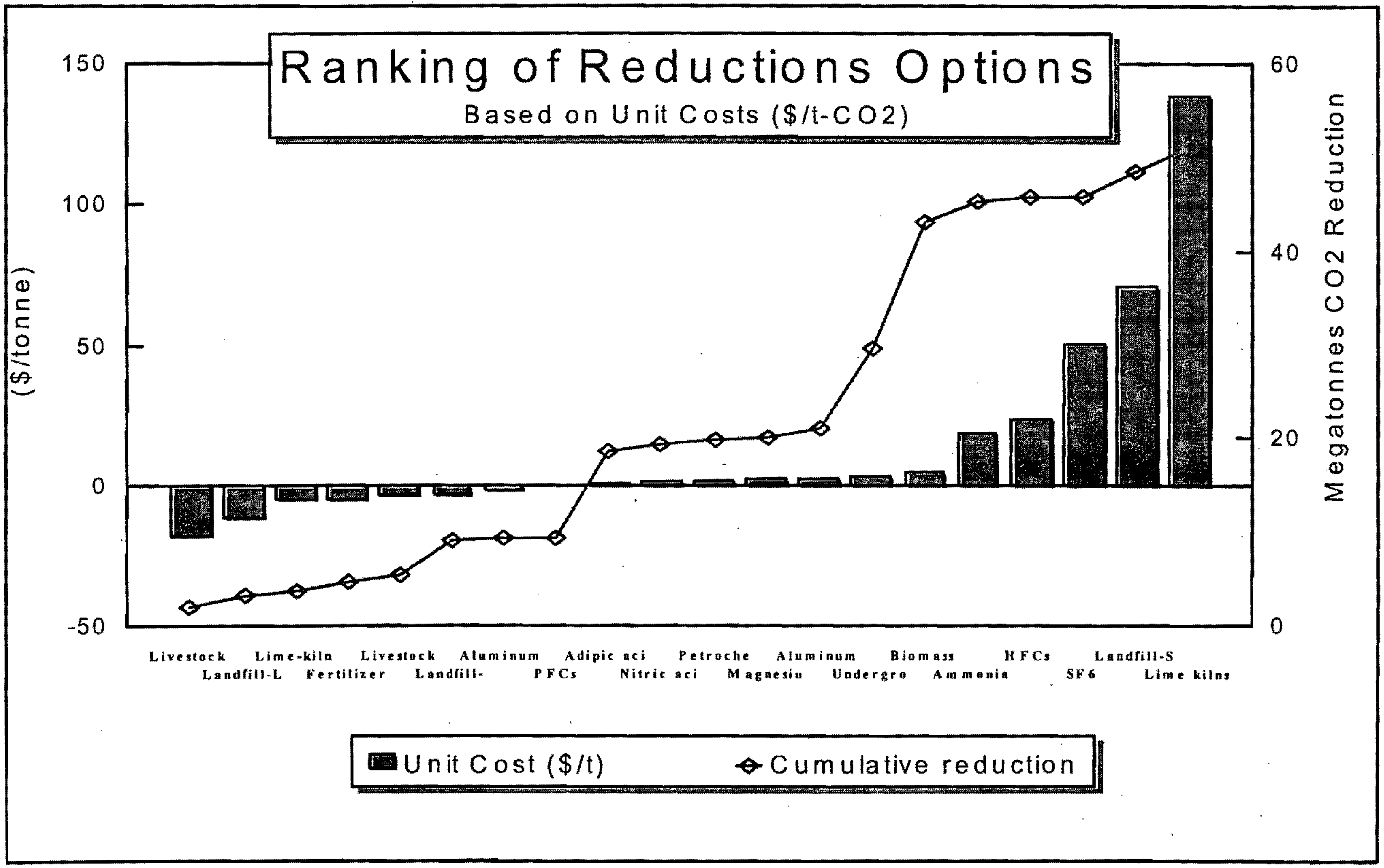
16.1.1 Total (Capital and Operating) Unit Costs

Unit reduction costs ($/tonne-$CO_2$) developed for this study are useful for ranking various options. However, these costs reflect chosen technologies, and may not be representative of the best technologies (energy and non-energy) that could be applied in each of the emitting areas.

Selected Technology Costs and Overall Reduction Levels

(Unit costs per tonne of CO_2 reduced: annualized capital plus operating costs)

Area / Segment	Technology Used for Costing	Overall Reduction	Reduction Costs (Benefits)
			(\$/t-CO_2)
Livestock: Enteric fermentation	Feed additives	4%	(\$18.0)
Landfill-Large	Electricity generation	35%	(\$12.0)
Lime-kiln: Cement	Flyash or slags for cement	10%	(\$5.0)
Fertilizers	Test and minimize use	22%	(\$5.0)
Livestock: Manure	Anaerobic digesters	13%	(\$4.0)
Landfill-Medium	Electricity generation	35%	(\$4.0)
Aluminum -anodes	Carbon anode improvements	5%	(\$2.0)
PFCs	Substitution with HFEs	50%	\$0.0
Adipic acid	Catalytic oxidation	86%	\$0.2
Nitric acid	Catalytic reduction	60%	\$1.3
Petrochemicals	Feedstocks substitution	35%	\$1.4
Magnesium-SF6	Substitution with SO2	10%	\$1.9
Aluminum-PFCs	Process control	20%	\$2.3
Underground storage	Enhanced oil recovery	7%	\$3.0
Biomass sequestration	Reforestation/afforestation	20%	\$5.0
Ammonia plants	Urea production	68%	\$18.6
HFCs	Alternative refrigerants	100%	\$23.5
SF6	Leak reduction	10%	\$50.2
Landfill-Small	Flaring	35%	\$71.0
Lime kilns	Capture and underground storage	60%	\$139.3


Ranking of Reductions Options
Based on Unit Costs ($/t-CO2)
150
100
50
0
-50
($/tonne)
60
40
20
0
Megatonnes CO2 Reduction
Livestock
Landfill-L
Lime-kiln
Fertilizer
Livestock
Landfill-
Aluminum
PFCs
Adipic aci
Nitric aci
Petroche
Magnesiu
Aluminum
Undergro
Biomass
Ammonia
HFCs
SF6
Landfill-S
Lime kilns
▨ Unit Cost ($/t)
◇ Cumulative reduction

16.1.2 Capital Costs

Some technologies can provide economic benefits, but have high capital costs (and costs of capital different than assumptions used for this study - i.e., 10% interest rate) that present barriers to increased adoption. The attractiveness of various technologies for development purposes or for adoption will be influenced by the total capital investment required to bring about a reduction. From a capital cost basis, the most attractive areas include: product substitution for PFCs; substitution of fly ash, slags and other suitable materials for cement clinker; farm practices to reduce fertilizer use; and biomass sequestration tactics such as reforestation and afforestation.

Areas which require more research and development to lower capital costs in the application of the technologies includes: lime kilns; small landfills; ammonia plants; digesters for livestock manure; and underground storage (with or without enhanced oil recovery). These areas which feature such problems as dilute carbon dioxide gas streams, fragmented pattern of emissions, lack of infrastructure and lack of markets present development challenges may need to be overcome for Canada to achieve reductions from non-energy sources approaching Kyoto targets.

Capital Costs For Selected Reduction Technologies

(ranked by annualized unit capital costs)

Area	Technology	% GHG Reduction	Total Capital Costs	Annualized Total Capital Costs	Unit Capital Cost
			(\$ million)	(\$ million)	(\$/t-CO_2)
PFCs	Substitution with HFEs	50%	\$0.0	\$0.0	\$0.0
Lime-kiln - Cement	Flyash or slags for cement	10%	\$0.0	\$0.0	\$0.0
Fertilizers	Test and minimize use	22%	\$0.0	\$0.0	\$0.0
Biomass sequestration	Reforestation/afforestation	20%	\$0.0	\$0.0	\$0.0
Aluminum -anodes	C anode improvements	5%	\$0.0	\$0.0	\$0.0
Adipic acid	Catalytic oxidation	86%	\$15.0	\$1.8	\$0.2
Nitric acid	Catalytic reduction	60%	\$3.0	\$0.4	\$0.5
Magnesium-SF6	Substitution with SO2	10%	\$3.0	\$0.4	\$1.9
Aluminum-PFCs	Process control	20%	\$22.0	\$2.6	\$2.3
Lime kilns	Underground storage	60%	\$100.0	\$11.7	\$4.3
Landfill-Medium	Electricity generation	35%	\$250.0	\$29.4	\$7.9
Landfill-Large	Electricity generation	35%	\$100.0	\$11.7	\$10.1
Petrochemicals	Feedstocks substitution	35%	\$100.0	\$11.7	\$21.4
HFCs	Alternative refrigerants	100%	\$100.0	\$11.7	\$23.5
Landfill-Small	Flaring	35%	\$800.0	\$94.0	\$35.4
Ammonia plants	Urea production	68%	\$760.0	\$89.3	\$41.6
SF6	Leak reduction	10%	\$10.0	\$1.2	\$45.2
Underground storage	Enhanced oil recovery	7%	\$4,600.0	\$540.3	\$63.0
Livestock:- Manure	Digesters	13%	\$615.0	\$72.2	\$96.3

16.1.3 Range in Costs

The total costs of applying a technology to a particular area can range based on many factors, including: GHG reduction level sought; portion of facilities adopting technology within a segment; competitive responses; and many other factors. For this analysis, a set of costs were developed reflecting the low cost assumption in the range of capital and operating costs. To provide a range of costs, high cost assumptions were also used, in some cases relating to higher levels of GHG reductions (at the technology level) and broader adoption of the technology to achieve high levels of GHG reduction. Direct costs for achieving even greater levels of reduction would be even higher.

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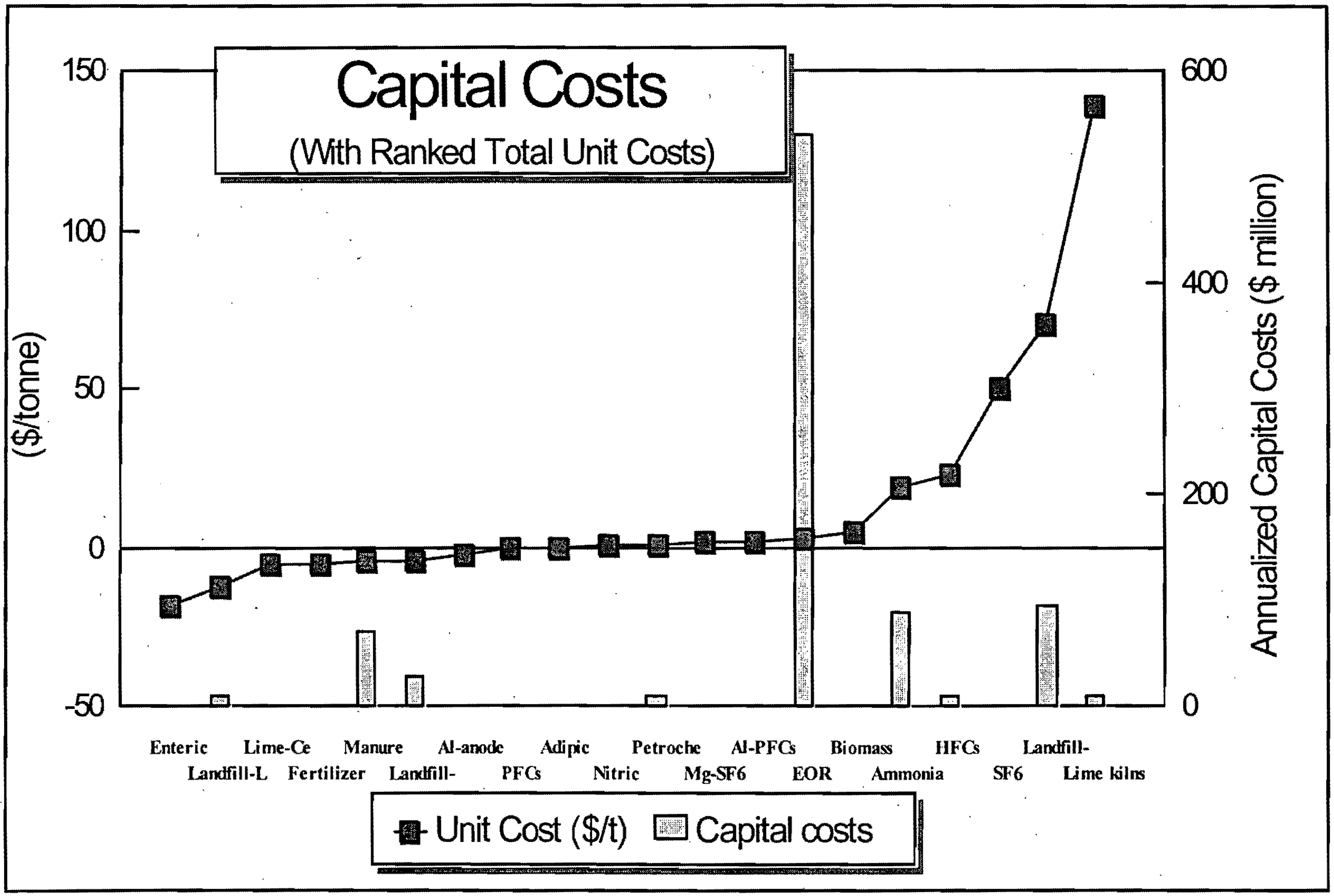
Capital Costs
(With Ranked Total Unit Costs)
150
100
50
0
-50
($/tonne)
600
400
200
0
Annualized Capital Costs ($ million)
Enteric
Landfill-L
Lime-Ce
Fertilizer
Manure
Landfill-
Al-anode
PFCs
Adipic
Nitric
Petroche
Mg-SF6
Al-PFCs
EOR
Biomass
Ammonia
HFCs
SF6
Landfill-
Lime kilns
Unit Cost ($/t)
Capital costs

16.2 Canadian R&D Capabilities

In a few areas, Canada's R&D status and capabilities are already strong. Fortunately, some of the these strengths lie in areas that are also major sources and sinks of GHG, namely the agricultural sector, forestry and pulp and paper, and oil and gas production. In many other areas, Canada's R&D capabilities are weaker, and in some cases practically non-existent with respect to technologies associated with reducing GHG emissions from non-energy areas (and investigated in this study).

Overview of Research and Development Capabilities in Canada

(in context of GHG technologies investigated)

Areas	Corporations	Industry R&D Centres	Government R&D Centres	Universities
Agriculture	●●	●●●	●●●●	●●●●
Landfills	●●	●	●●	●
Adipic acid	●●	●	●	●
Lime kilns	●	●	●	●
Aluminum	●●●	●	●	●●
Petrochemicals, other chemicals	●●	●	●	●
SF_6, HFCs, PFCs	●●	●●	●●	●●
Nitric acid	●●	●	●	●
Biomass sequestration	●	●	●●●●	●●●
Underground storage (EOR)	●●	●●	●●	●●

Legend:	●	very weak or non-existent
	●●	some research conducted
	●●●	strong research capability
	●●●●	very strong, among world leaders in field

Given the dynamics of global competition in many industrial areas, Canadian foreign-owned subsidiaries have access to R&D centres of their parent companies. For multi-national enterprises, these R&D centres are often located near the parent head-offices. Examples of this structure of R&D supply and demand include technologies (and associated GHG emitting sectors) in the following areas: gas separation needed for lime kilns and other areas; cement; catalyst technologies (adipic acid, nitric acid); magnesium production (SF_6); and refrigerants (HFCs). There are "pockets" of R&D activities in most of these fields carried out in Canada. However, the overall mass of activity and resources available are low in comparison to what is carried out internationally.

To facilitate scoping of development efforts, technologies covered in this study are summarized as to their status (in terms of development) and R&D requirements. These requirements cover product and process research as well as market and commercial development needs. In many cases, marketing efforts will play a more important role in commercialization and adoption. The status is categorized on a scale of A to J, as follows.

Elements of Technology Research and Development

Status	Requirements	Category
Product Research & Development		
Concept Stage	Vision of benefits	A
Laboratory, bench scale	Basic research	B
Pilot plant, scale-up	Design, engineering	C
On-site demonstration	Potential customer partners	D
Technical improvements for broad application	Redesign, re-engineering	E
Market and Commercial Development		
Testing at customers' facilities	Interested potential customers	F
Minor (or niche) market position	Unique customers	G
Competitive with alternative technologies	Dynamic market mechanisms	H
Market domination	Major technical, cost advantages	I
Transfer (export, cross-cutting applications)	Global marketing, financing	J

Technologies can be grouped into two general categories namely: those that require product research and development, and those that require market and commercial development. Nearly two thirds of the technologies identified and investigated in this study require greater marketing and commercial development. Generally, these technologies have been adopted to varying degrees by the market place. The rest of the technologies generally require product developments to address technical issues and lower costs to encourage some or broader application.

Many of the technologies and practices identified in this study have very low market penetration, and in some cases no current use in Canada. In general, there is currently no substantial incentive for emitters to adopt GHG emission reduction technologies. In those situations where an economic incentive has been identified (at the same time reducing GHG emissions), technology has been adopted. Landfill gas from large sites for electricity generation or heating is a case in point. However, application of energy utilization projects and gas flaring at landfills has not been focused on reducing GHG emissions.

Technologies Status and Requirements Summary

1	Livestock: Enteric Fermentation	
1.1	Improved Cow-Calf Productivity	G
1.2	Ionophores	G
1.3	Hormones and Steroids	H
1.4	Bioengineering	D
1.5	Twinning	F
1.6	Bioengineering Rumen Microbes	F
1.7	Transgenic Manipulation	G
2	Livestock: Manure	
2.1	Covered Lagoons	E
2.2	Large Scale Digesters	
2.2.1	Plug Flow Digesters	G
2.2.2	Complete Mix Digesters	G
2.3	Small Scale Digesters	
2.3.1	Floating Gas Holders	B
2.3.2	Flexible Bag Holders	B-C
2.3.3	Fixed Dome	B-C
2.4	Slurry Digesters	B
2.5	Mesophilic Digesters	B
2.6	Other Types of Digesters	A-B
2.7	Constructed Wetlands	G
2.8	Liquid Manure Recycling	C
2.9	Bioreactors	B
3	Fertilizers	
3.1	Fertilizer Management Practices	F
3.2	Nitrification Inhibitors	G
3.3	Irrigation Water Management	C
3.4	Organic Farming	G
3.5	Substitution Among Fertilizers	A-B
4	Landfill Gas	
4.1	Gas Collection and Treatment	G
4.2	Flaring	H
4.3	Methane Utilization	H
4.3.1	Electricity and Steam Generation	H
4.3.2	Fuel To Nearby Users	G
4.4	Reduced waste generation and landfilling	H
5	Adipic Acid Production	
5.1	Catalytic Reduction of Nitrous Oxide	I-J
6	Lime Production	
6.1	Pulp and Paper Production	
6.1.1	Ethanol Based Pulping	C
6.1.2	Modified Continuous Cooking- MCC	H
6.1.3	Oxygen Delignification	H
6.1.4	Ozone Delignification	G
6.1.5	Enzymes	G
6.1.6	Closed -Cycle Bleached Kraft Mills	F
6.1.7	Upgrading Mechanical Pulps	A-G
6.1.8	Carbon Dioxide Use at the Kraft Pulp Mills	G
6.1.9	Paper Recycling and Deinking	H
6.2	Portland Cement Manufacturing	
6.2.1	Use of Fly Ash in Cement	E-G
6.3	Merchant Lime Producers	
6.3.1	Treatment	
6.3.1.1	Cryogenics (in context of lime / broad market	A / H
6.3.1.2	Pressure Swing Adsorption (and Vacuum PSA)	B / H
6.3.1.3	Membrane Systems	B / H
6.3.2	Sequestering and Disposition of Carbon Dioxide	
6.3.3	Sequestering CO2 in Carbonates	A
6.3.4	Sequestering CO2 in Cement	B
6.3.5	Acid Markets	G

7	Petrochemicals	
7.1	NGLs and Crude Oil Feedstock Based Petrochemicals	
7.1.1	Anticoking Additives	H
7.1.2	Alternative Feedstocks	H
7.1.3	Loss Prevention and Other	H
7.2	Methane Based Petrochemicals	
7.2.1	Increasing Urea Production Using Ammonia	H
7.2.2	Increasing Methanol Production Using Hydrogen	H
7.2.3	Energy Efficiency Improvements	H
8	Nitric Acid Production	
8.1	Catalytic Reduction	I-J
8.2	Thermal Reduction	B
8.3	Change in Catalyst Precious Metal Content	H
8.4	Post Reaction Heat Exchange System Changes	A-B
9	Aluminum Production	
9.1	Inert Anodes	B
9.2	Replacement with Prebake Anode Technology	H
9.3	Improved Alumina Feed Process Control	H
10	Magnesium Production	
10.1	Reducing Utilization Rate - Improved Control	H
10.2	Replace Blanket Gas Component	C
11	SF6, PFCs and HFCs for Other Uses	
11.1	SF6	
11.1.1	Improved Recycling from Electrical Switchgear	H
11.1.2	Air or Vacuum Insulated Circuit Breakers	H
11.2	PFCs	
11.2.1	Substitution - Hydrofluoroethers (HFEs)	G
11.2.2	Capture and Recycling	H
11.3	HFCs	
11.3.1	Other HFCs	A-B
11.3.2	Hydrocarbons	E-H
11.3.3	Ammonia	E-G
11.3.4	Carbon Dioxide	B
11.3.5	Water/Zeolite Adsorption Systems	B
11.3.6	Stirling Cycle	B
11.3.7	Air Cycle Systems	A
12	Carbon Sequestration in Biomass	
12.1	Reforestation and Afforestation	G-H
12.2	Agroforesty	G-H
12.3	Forest Protection	G-H
12.4	Management of Logging Residues, By-Products	G-H
12.5	Protection Against Fire	G-H
12.6	Protection Against Disease, Pests, Herbivores	G-H
12.7	Salvage of Dead and Dying Trees	G-H
12.8	Biomass Energy	G-H
12.9	Urban Forestry	G-H
12.9.1	Forest Management	G-H
12.9.2	Reduced Impact Logging	G-H
13	Underground Reservoirs (Enhanced Oil Recovery)	
13.1	Capture, Treatment and Extraction	D-F
13.2	Salvage of Dead and Dying Trees	G-H
13.3	Biomass Energy	G-H
13.4	Urban Forestry	G-H
13.4.1	Forest Management	G-H
13.4.2	Reduced Impact Logging	G-H
14	Underground Reservoirs (Enhanced Oil Recovery)	
14.1	Capture, Treatment and Extraction	D-F

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