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ASSESSMENT OF NET EMISSIONS OF GREENHOUSE GASES FROM ETHANOL-GASOLINE BLENDS IN SOUTHERN ONTARIO

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EXECUTIVE SUMMARY

The agricultural and road transportation sectors are significant sources of greenhouse gas emissions in Canada. The agriculture and agri-food sector accounts for approximately 15% of Canada's annual emissions (roughly 14% can be attributed to primary agriculture with processing of food and fibre accounting for approximately another 1%). Emissions of greenhouse gases from Canadian road transportation sources in 1995 totalled approximately 123 Mt (Jaques et al, 1997). This amounts to about 19.9% of the total CO_2 equivalent greenhouse gas emissions from energy and non-energy sources in 1995 (23.8% if considering only energy sources) and about 74.3% of the total greenhouse gas emissions from the Transportation Sector. The greenhouse emissions from the road transportation sector arise 51.1% from automobiles, 26.0% from heavy-duty trucks and buses and 22.8% from light-duty trucks, with the remainder being from motorcycles.

In December 1997, the parties to the 1992 United Nations Framework Convention on Climate Change (FCCC) adopted a protocol to the Convention (the Kyoto Protocol) to limit emissions of greenhouse gases. The Protocol will come into force when fifty-five countries covering a minimum of fifty-five percent of the FCCC Annex 1 countries emissions, have ratified the protocol. Canada is an Annex 1 country and has accepted a GHG reduction target of six percent below its 1990 level of 564 Mt (CO_2 equivalents) by the end of the first reporting period, 2008-2012. Canada and a number of other countries have not yet ratified the Kyoto Protocol.

Analysis conducted by Environment Canada indicates that net GHG emissions in Canada will need to be reduced by 21-26 percent under a business-as-usual scenario to achieve the six percent reduction target. This is a difficult challenge for Canada given its growing population, cold climate, long transportation distances, and the fact that our exported raw materials contain significant embedded fossil fuel emissions.

The production and use of renewable fuels manufactured from agricultural feedstocks, such as corn, is one greenhouse gas emission reduction opportunity that could offer a synergistic benefit to the agricultural and transportation sectors. A number of studies have been performed for the United States on the life-cycle greenhouse gas emissions of ethanol produced from corn that have shown this fuel system has a positive energy balance and will result in a reduction in greenhouse gas emissions. This study was undertaken to provide an analysis of the life-cycle emissions and life-cycle energy balance of the production of ethanol from corn and its subsequent use as a motor fuel in blends with gasoline. The study focuses specifically on Southern Ontario, which is the largest corn growing area in Canada, as well as one with a large demand for motor gasoline. Energy and emission analysis was conducted in this study for a base case ethanol production volume of 225 ML per year in 2000 and 2010. Further analysis was done to investigate the effects of annual ethanol production volumes of 500 ML, 750 ML and 1,000ML.

Corn production in Ontario is typical of corn production in the United States. The use of agricultural chemicals in Ontario is lower than it is in the US but so is the yield of corn. Energy use on the farm is higher in Ontario than in the US, apparently due to higher consumption of energy for crop drying. Overall energy use to produce corn is lower than most areas of the United States due to the extensive use of manure as a source of nitrogen in Ontario.

The energy consumed by ethanol plants in Ontario is higher than similar plants in the United States. This does not appear to be caused by any design differences, but rather by more operating experience at the American plants. It is anticipated that over time the energy used by the ethanol plants in Ontario will drop substantially and be on a par with other similar plants in North America.

Ethanol produced from corn in Ontario and blended with gasoline will reduced emissions of greenhouse gases. The current situation of 150 million litres of ethanol produced in a large modern plant and blended into gasoline taking full advantage of ethanol's octane rating reduces greenhouse gas emissions by 3.9% compared to gasoline. Ethanol production in Ontario is expected to become more efficient as operating experience is obtained, so that by 2010 it is expected that 10% ethanol blended gasoline will reduce GHG by 4.6%. If ethanol production can be expanded to one billion litres per year by 2010 then emissions of GHG can be reduced by 1.47 million tonnes annually. This represents 0.8 to 1.0% of the total reduction required to meet Canada's commitment to the Kyoto Protocol.

Producing ethanol has a net positive energy balance. Ethanol when used as a 10% blend in the year 2000 has a net effective energy content of 43,800 BTU/US gallon of ethanol. This represents 52% of the energy contained in the fuel. Gasoline by comparison has a net energy content of 76% of the energy contained in the fuel. Stated another way, 24% of the energy contained in crude oil is used to produce it, refine it to gasoline, and move it the consumer. By the year 2010 with the advent of low sulphur gasoline which requires more processing energy offset by continuing improvement in oil refining efficiency the net energy content of gasoline is expected to decline to 75% of the energy in the fuel. Ethanol's net effective energy content is expected to improve by 2010 to 63% of the energy in the fuel due primarily to more energy efficient manufacturing operations.

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BTU	British Thermal Units Energy. To convert to kJ multiply BTU by 1.055
bu	Bushel
CAI	Commercial Alcohols Inc.
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 Equivalent	Weighted sum of CO_2, CH_4 and N_2O emissions using the weighting GWP factors defined below.
CPPI	Canadian Petroleum Products Institute
DDGS	Distillers dried grains with solubles. Also sometimes abbreviated as DDG.
E10, E85 & E100	10%, 85% and 100% ethanol with balance gasoline by volume, respectively
g	Gram
gal	US gallon (3.785 L)
GHG	Greenhouse gases
GJ	Gigajoule (10^9 Joules)
GWP	Global warming potential over a 100 year period: CO_2, 1; CH_4, 21; N_2O, 310
ha	Hectare (10,000 square meters)
HHV	Higher heating value of a fuel (combustion moisture as liquid)
k	Prefix for thousand
km	Kilometre
L or l	Litre
lb	Pound (0.4536 kg)
M	Prefix for million, when used with metric unit
mi	Mile (1.609 km)
MM	Million when applied to an imperial unit of energy
mpg	Mile per United States gallon
NMOG	Non-methane organic gases
NRCan	Natural Resources Canada
N_2O	Nitrous oxide
NO_x	Oxides of nitrogen
PJ	Petajoule (10^{15}J)
PM	Particulate matter
ppm	Parts per million by volume
SBM	Soy Bean Meal
SME	Soy methyl ester
S	Sulphur
SIE	Spark ignition engine
SO_2	Sulphur dioxide
t	Tonne (1000 kg)
THC	Total hydrocarbon
US	United States of America
VOC	Volatile organic compounds, excluding methane and ethane

1. INTRODUCTION

1.1 BACKGROUND

Under the Kyoto Protocol, Canada committed to reduce GHG emissions by 6% from 1990 levels by the period 2008 to 2012. The agriculture and agri-food sector accounts for approximately 15% of Canada's annual emissions (roughly 14% can be attributed to primary agriculture with processing of food and fibre accounting for approximately another 1%). Table 1-1 summarizes agricultural GHG emissions for 1991. These numbers do not include emissions associated with the distribution of commodities from the farm to processing centres and ultimately to consumers; such emissions are attributed to the transportation sector.

Table 1-1 Agricultural GHG Emissions for 1991

	Emissions Mt	Emissions CO_2 equivalent Mt	Percent of Canadian Totals
Carbon Dioxide	27.8	27.8	6.1
Methane	0.951	20.0	29.8
Nitrous Oxide	.11	34.3	12.8
Total		82.2	14.7

Transportation represents the single largest source of Canada's GHG emissions, accounting for 27 per cent of the total. Transportation emissions arise from all sectors of the commercial economy and are inherent to the movement of people and goods for commercial, social and recreational activities. Hence, measures to reduce emissions from the transportation sector must be considered very carefully and respect the ramifications of such measures on the economy and peoples day-to-day activities. Emissions from transportation are growing faster than the average for all emissions and are forecast to exceed 1990 levels by 26 per cent in 2010 and 42 per cent by 2020 (NRCan 1997).

It is clear that both the transportation sector and the agriculture sector have significant roles to play in helping Canada meet its objectives under the Kyoto Protocol. One strategy that holds promise for both sectors is the production and use of renewable fuels manufactured from agricultural feedstocks such as corn. A number of studies have been performed in the United States on the GHG emissions of ethanol produced from corn. The recent studies have shown significant GHG reductions and a positive net energy balance. Canada has a different mix of energy sources than the US and the ethanol industry is just beginning to develop in this country. It is not clear that the results from US studies are directly applicable to Canada.

Typically, about 72% of greenhouse gas emissions arising from a gasoline-fuelled motor vehicle originate from the tailpipe, 21% from fuel supply and 7% from vehicle manufacture. Improvements in the fuel economy of vehicles will reduce emissions from the tailpipe and from fuel manufacturing and delivery for a given type of fuel/vehicle system. Because of the contribution made by the fuel manufacturing and delivery system to the total emissions associated with motor vehicle use, it is essential that analysis of fuel/vehicle transportation options consider full cycle or lifecycle greenhouse gas emissions.

For a full cycle analysis of greenhouse gas emissions for corn ethanol the following types of emission sources need to be considered:

- manufacturing and distribution of fertilizers, herbicides, insecticides and fuels used for growing corn;
- conversion of applied nitrogen fertilizer to N_2O and emissions associated with farming practices (tilling, irrigation, etc.);
- ethanol plant energy use and co-product quantities and usage. Co-products associated with ethanol production from corn include distillers dried grains with solubles (DDGS), wet distillers grains (WDG), and carbon dioxide;
- ethanol blending in gasoline and the effects on refinery energy efficiency if steps are taken to optimize refinery processes for ethanol;
- ethanol combustion in the motor vehicle fleet, with allowance for the effects on vehicle fuel economy.

There have been a number of published and unpublished studies of full cycle greenhouse gas emissions from the manufacture and use of corn ethanol. These have mostly been done in an American or European context. The results from these studies have also varied widely as the results are very sensitive to inputs, assumptions and methodology. It is therefore important to have a publicly accessible Canadian study that uses the best data available and applies sound scientific methodology to provide a basis for informed public policy decisions. The purpose of this study is to meet that need and to determine the GHG emissions resulting from ethanol gasoline blends produced in Canada from Ontario corn. The results are compared to gasoline production typical of the fuel manufactured in Southern Ontario's five refineries.

1.2 Description of Study Region

Southern Ontario is the region between the US border on the south, Quebec on the north and bounded by the Great Lakes on the east and west. This region is the major corn growing region of Canada and is also one of the most populated areas of Canada. Five oil refineries serve it. It has Canada's largest fuel ethanol plant and fuel-ethanol marketing network. If the ethanol is used as a 10% blend and manufactured from Ontario corn then it also has the potential to manufacture and use up to six times the ethanol that is currently being produced in the region. Significant market penetration of E85 vehicles or exports of ethanol, imports of corn, or breakthroughs in corn production technology could lead to an even larger industry.

Before this potential is realized, it is important to fully understand the implications of expanded corn ethanol production and use on the energy balance and greenhouse gas emissions from such a fuel option. It is therefore an ideal study region to model the GHG emissions associated with corn derived ethanol and Canadian gasoline.

1.3 Scope of Work

The work completed by the project team was designed to accomplish the following objectives:

1. Determine the lifecycle energy balance for the production of ethanol from corn in southern Ontario. The analysis will take into account the energy credits for co-products from the ethanol production process, and be based on farming data for the Southern Ontario region and operating and design data for the Commercial Alcohols Inc. (CAI) plant in Chatham, Ontario.
2. Determine the energy balance for the production of gasoline in southern Ontario refineries, documenting energy requirements for production and that released during combustion.

3. Determine the impact on greenhouse gas emissions of using ethanol blended gasoline in blends of 6%, 8%, 10%, and 85% compared to conventional gasoline. Emissions of carbon dioxide, methane and nitrous oxide must be considered for all aspects of the lifecycle from production through to end-use. The assessment must be quantitative and incorporate both corn production and gasoline refining/ethanol blending. Greenhouse gas emissions are to be reported for individual gases and as combined CO_2 equivalent emissions.

4. Estimate energy balances for the specified ethanol blend cases for the year 2010 using the following assumptions:

   - ethanol consumption in gasoline increases from 225 ML in 1999 to 500, 750 and 1,000 ML in 2010;

   - there will be continuing improvements in technology for corn production, ethanol and gasoline production but no breakthroughs in technologies such as conversion of corn fibre to ethanol;

   - In addition, relate the reduction in greenhouse gas emissions achieved in the future to Canada's commitment under the Kyoto Protocol.

5. Identify data gaps and uncertainties with respect to the analysis of greenhouse gas emissions from corn ethanol production, gasoline manufacturing and use of gasoline and ethanol blended gasoline in Southern Ontario.

2. General Approach and Methodology

2.1 Overall Approach Used for the Study

The objectives of the study require the development of reliable estimates of the energy use and greenhouse gas emissions associated with production and use of gasoline and ethanol/gasoline blends in motor vehicle applications. With this information, the net effect on energy consumption and greenhouse gas emissions of ethanol-gasoline blends can be determined.

The third main area of consideration for ethanol production and use is the effect of ethanol-gasoline blends on the fuel economy of on-road motor vehicles. Published literature was used as the source of information on the effect of ethanol's fuel properties on the thermal efficiencies of current internal combustion engines and the associated effects on pollutant emissions.

Lifecycle energy use and greenhouse gas emissions for gasoline are the reference for comparison in this study. We considered all stages in the lifecycle of gasoline from crude oil production, through to refining and use in a motor vehicle. The energy used for refining has been modeled considering the five refineries present in Southern Ontario and their typical crude oil supply mix. The methods used for the analysis are discussed later in this chapter. Also considered was the effect of the use of ethanol as a source of gasoline octane on the energy balance of a representative refinery in Southern Ontario.

The analysis is based on producing ethanol from corn in Southern Ontario and, hence, needs to consider the corn yield, farming practices and resource supply issues for this region. Corn is presumed to be converted to ethanol using proven technology of the type and design used at the plant operated by CAI, in Chatham, Ontario. Data was obtained for this plant with the co-operation of CAI, allowing the analysis to model the energy use, product and by-product yields, greenhouse gas emissions accurately. Distillers dried grains with solubles are an important by-product of ethanol production and are used as a component of feed for beef and dairy cattle, displacing some corn and soybean meal commonly used for this purpose. The analysis in this study has considered the reduction in lifecycle greenhouse gas emissions achieved when DDGS displace corn and soybean meal as animal feed.

This study considered two time frames, 2000 and 2010 and four ethanol production volume scenarios, 225 ML/yr, 500 ML/yr, 750 ML/yr and 1,000 ML/yr. The potential reduction in greenhouse gas emissions was determined for each scenario based on the gasoline sulphur content appropriate for each time period. Trends in energy efficiency improvements have been included in the analysis for 2010.

2.2 Overview of Full Cycle Concept for Gasoline and Ethanol Blends

The full cycle concept of analyses considers all inputs into the production and use of a fuel. It combines the fuel production, vehicle manufacture and fuel use in a single analysis (see Figure 2-1.) It is also referred to as the fuel cycle by some authors. The ultimate result is a value that can be used for comparison of different commodities on the same basis, such as per unit of fuel energy or per kilometre driven. Greenhouse gas emissions over the full cycle include all significant sources of these emissions from production of the energy source (i.e. crude oil, biomass, natural gas, etc.), through fuel processing, distribution, and onward to combustion in a motor vehicle for motive power. A life cycle analysis should also include greenhouse gas emissions from vehicle material and assembly as these emissions are affected by the choice of alternative fuel/vehicle technology. Wide ranges of emission sources are involved in the production and distribution of fuels, and these vary depending on the type of fuel.

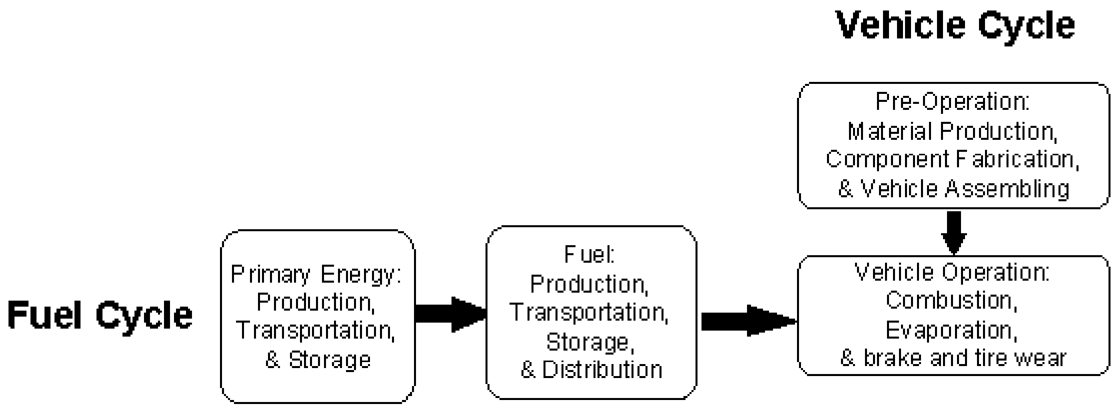

Figure 2-1 Full Cycle including Fuel and Vehicle Cycles

The two fuel pathways of interest here are petroleum to gasoline and corn to ethanol (Figure 2-2). The ethanol is subsequently blended with gasoline in various proportions. The final comparison is gasoline to ethanol blended gasoline.

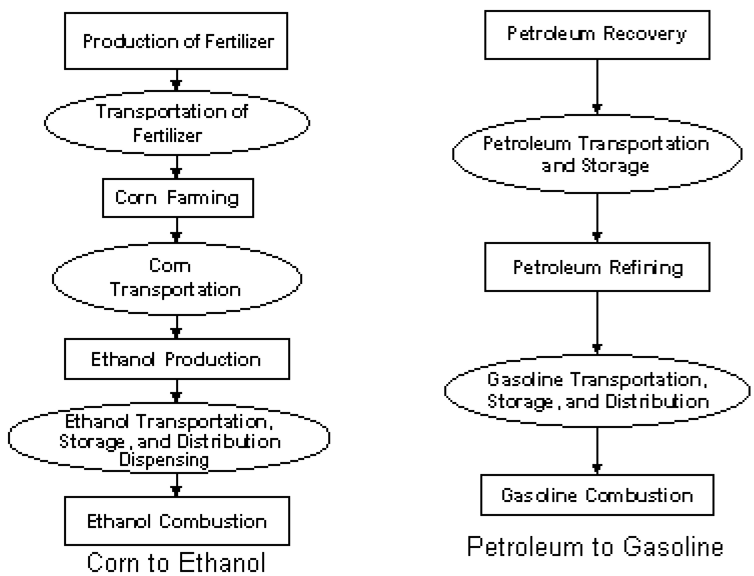

Figure 2-2 Corn to Ethanol and Petroleum to Gasoline Fuel Cycles

2.3 FULL CYCLE AND ENERGY BALANCE ANALYSIS METHODS

Two spreadsheet models are available from the United States to facilitate full cycle emission analysis; one developed by Delucchi (1991,1993, 1998), the other by Wang (1996). The work of Delucchi in the 1987-1993 period resulted in the development of a spreadsheet model based on Lotus software for Apple™ computers, which contained capabilities for predicting emissions of greenhouse gases and criteria non-greenhouse gases from most of the alternative fuels of potential interest in this study. The model is comprehensive in scope and level of detail, and, hence, requires input of extensive information on the energy usage for fuel production, distribution and related fuel cycle sources, as well as factors for emissions of non-greenhouse gases from these sources and motor vehicles. Using the results from the Delucchi model and a simplified approach based on the application of energy conversion efficiencies and relative emission factors for emissions from the full cycle sources, Wang (1996) developed a more user-friendly spreadsheet model for the US DOE in Excel™. This model is available on the Internet at www.anl.org.

Delucchi has updated his model since 1993, as described in Delucchi and Lipman (1996) and a report by Energy and Environmental Analysis Inc. (1999). This work has focused primarily on updating the earlier model to include recent data for motor fuel production, processing, distribution and use in the United States, and incorporation of improved algorithms for predicting non-greenhouse gas emissions from motor vehicles based on the U.S. EPA Mobile 5 model. A partial Canadianization of the Delucchi model was completed by Delucchi (1998) for Natural Resources Canada (NRCan) in late 1998 through to March, 1999, drawing from information on the production and distribution of conventional and alternative fuels that was provided by NRCan and Statistics Canada and some other Canadian government agencies.

The partially Canadianized version of the full cycle model prepared by Delucchi in 1998 was further developed by Levelton (1999) for NRCan. This Canadianized version was selected for use as the starting point for this study. It was considered to yield the most rigorous life cycle analysis of both greenhouse and non-greenhouse gases from alternative motor fuels, and had the advantage of incorporating functional capabilities and data for analysis of Canada specifically. The parameters used in the model for predicting emissions from gasoline and ethanol production and use were further refined to accurately simulate full cycle emissions in the study area. The model utilizes the higher heating value (HHV) for the energy content of all fuels.

2.3.1 Greenhouse Gases Included

The greenhouse gases include in the calculations for this report are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The emissions have been weighted according to IPCC guidelines where CO_2 has a weighting factor of 1.0, CH_4 is assigned a value of 21.0 and N_2O has a weighting factor of 310. These are the 100-year global warming potential (GWP) multipliers recommended by the IPCC. Throughout the report we will report primarily CO_2 equivalent values. This will be the weighted sum of the three greenhouse gases. In some areas this will be further broken down to provide detail on the separate gases.

Other gases and contaminants associated with the production and use of fossil and renewable fuels, such as carbon monoxide, non-methane organic gases, oxides of nitrogen and particulates, also have the potential to influence climate change, either directly or indirectly. The global warming potential of these other gases has not been considered in this study, to be consistent with the approach being used by the National Climate Change Secretariat.

2.3.2 Gasoline

The study team conducted a review of the Ontario refineries in terms of capacity, crude oil types processed, processing units employed and products produced. The greenhouse gases typically released during the production of the crude oil slate used in Ontario were calculated from published data from the Canadian Association of Petroleum Producers (CAPP 1998). The model was then calibrated to produce data consistent with the CAPP emission factors.

The energy used to make gasoline in a refinery that is representative of the plants in Ontario was determined from energy consumed by each refinery unit operated at an industry standard efficiency. This information was derived from the files of the study team and with selected interviews with Southern Ontario refiners. The study team also developed an estimate of the energy required for future gasoline production from analysis of the processing requirements.

Data from the foundation paper for the downstream petroleum industry, (Purvin & Gertz 1999) was used to verify the incremental refinery energy use in 2010 when low sulphur (30 ppm sulphur) gasoline will be required. Interviews with Canadian refiners provided insight into expected energy efficiency improvements in the refineries over the next decade.

Results were compared against published Canadian Refining Industry averages (Nyboer).

2.3.3 Ethanol and Ethanol Blends

A review of the CAI plant design and operating data was conducted for energy and raw material inputs and product outputs. This 150 million litre per year dry milling facility was started up in late 1997. The collected data was checked against published information from similar plants in the US. A substantial review of DDGS was undertaken both in the literature and with visits to cattle feeders with substantial experience feeding the product.

The study team made their own conservative estimates of efficiency improvements likely over the next decade as existing plants matured and new plants were built to fill projected demand. The assumed improvements were within the boundaries established by existing ethanol production technology. Thus by 2010 Canadian plants would be as efficient as the more efficient American plants in 1999.

Ethanol blends were analyzed by incorporating ethanol at several levels into our typical refinery. Corrections were made to balance the octane produced at the refinery.

2.4 Corn Production Analysis Methods

Visits to the Ontario Corn Producers Association and a review of the literature were used to determine the corn production practices in Ontario and the resultant energy inputs. Some published data was verified with the authors.

Energy consumption data for the farming sector in Canada are neither as widely available, nor as detailed, as US data. Intermediate results and calculated emissions were checked against published data from the United States to verify the accuracy of the Canadian data.

2.5 Motor Vehicle Emission Analysis Methods

The primary emphasis of the study was on life-cycle energy balances and greenhouse gas emissions. The fuel economy of motor vehicles and the effect of ethanol on fuel economy are important inputs to the analysis. The impact of ethanol on vehicle fuel economy on an energy basis was determined from the literature.

Emissions of regulated pollutants such as carbon monoxide, nitrogen oxides, VOC's, particulates and sulphur oxides can be calculated by the model. The methodology used is a modified version of the Mobile 5 model developed by the US EPA. This model is in the process of being updated by the US EPA, and one of the most significant changes is with how the model deals with oxygenated fuels and carbon monoxide emissions. This change is being driven by the fact that Mobile 5 overestimates the reduction in ambient air levels of carbon monoxide that areas experience with mandatory oxygenated fuels programs. The study team has chosen conservative values for the impact of ethanol on exhaust emissions because of uncertainty over the results that Mobile 6 will produce for oxygenated gasolines.

2.6 MODEL USED TO CALCULATE FULL CYCLE EMISSIONS

The Delucchi model, as used in this study, is capable of estimating fuel cycle emissions of the primary greenhouse gases, carbon dioxide, methane, nitrous oxide, and the criteria pollutants, nitrogen oxides, carbon monoxide, sulphur oxides, nonmethane organic compounds (also known as VOCs) and exhaust particulate matter. The model also is capable of analyzing the emissions from gasoline and alternative fuelled internal combustion engines for both light-duty and heavy-duty vehicles, and for light duty battery powered electric vehicles.

The full cycle model predicts emissions for past, present and future years using historical data or correlations for changes in energy and process parameters with time that are stored in the model. The model is thus capable of analyzing what is likely to happen in future years as technologies develop. The model allows for segmentation of the predicted emissions into characteristic steps in the production, refining, distribution and use of fuels and the production of motor vehicles. The fuel cycle segments considered in the model are as follows:

- Vehicle Operation
  Emissions associated with the use of the fuel in the vehicle. Includes all three greenhouse gases.
- Fuel Dispensing at the Retail Level
  Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive emissions and spills.
- Fuel Storage and Distribution at all Stages
  Emissions associated with storage and handling of fuel products at terminals, bulk plants and service stations. Includes storage emissions, electricity for pumping, space heating and lighting.
- Fuel Production (as in production from raw materials)
  Direct and indirect emissions associated with conversion of the feed stock into a saleable fuel product. Includes process emissions, combustion emissions for process heat/steam, electricity generation, fugitive emissions and emissions from the life cycle of chemicals used for ethanol fuel cycles.
- Feedstock Transport
  Direct and indirect emissions from transport of feedstock, including pumping, compression, leaks, fugitive emissions, and transportation from point of origin to the fuel refining plant. Import/export, transport distances and the modes of transport are considered.
- Feedstock Production and Recovery
  Direct and indirect emissions from recovery and processing of the raw feedstock, including fugitive emissions from storage, handling, upstream processing prior to transmission, and mining.
- Fertilizer Manufacture
  Direct and indirect life cycle emissions from fertilizers, and pesticides used for feedstock production, including raw material recovery, transport and manufacturing of chemicals.
- Land use changes and cultivation associated with biomass derived fuels
  Emissions associated with the change in the land use in cultivation of crops, including N_2O from application of fertilizer, changes in soil carbon and biomass, methane emissions from soil and energy used for land cultivation.
- Carbon in Fuel from Air
  Carbon dioxide emissions credit arising from use of a renewable carbon source that obtains carbon from the air.
- Leaks and flaring of greenhouse gases associated with production of oil and gas
  Fugitive hydrocarbon emissions and flaring emissions associated with oil and gas production.
- Emissions displaced by co-products of alternative fuels

Emissions displaced by DDGS, a co-product of ethanol production, equal to emissions from corn feed and soybean meal displaced net of emissions from transport of the product to the end-users.

- Vehicle assembly and transport

  Emissions associated with the manufacture and transport of the vehicle to the point of sale, amortized over the life of the vehicle.
- Materials used in the vehicles

  Emissions from the manufacture of the materials used to manufacture the vehicle, amortized over the life of the vehicle.

Levelton (1999) conducted a thorough review of the assumptions and characteristic parameters used in the original model to predict fuel cycle emissions from the fuels chosen in this study for detailed analysis. These assumptions and parameters were compared to information available to Levelton from in-house information, direct contact with energy and vehicle companies, published literature and other sources.

For this study further changes were made to the characteristics of the model to more accurately predict fuel cycle emissions in Ontario. A more in-depth review of land use changes, soil sinks and emissions, co-product credits and the implications of integration of ethanol into a refinery were made. A summary of changes to the model and the input parameters is shown in Appendix B.

Fuel economy in units of miles per US gallon is the principal input variable available to the user of the model for case studies and is used within the model as the energy demand that must be satisfied by the fuel production, refining and other segments of the fuel cycle. Fuel economy values are input separately for city and highway travel and for light-duty and heavy-duty vehicles. The model inputs are all in US units. Most of the full cycle energy and greenhouse analyses found in the literature use US units. We have presented results in US units and in most cases present input data in metric and US units.

3. Ethanol Production and Use

3.1 Overview of Farming and Ethanol Production

The basis of the study is the current corn farming practices in Ontario and the existing ethanol production practices at the CAI plant in Chatham Ontario. As described below, the most current data has been used to determine the appropriate model inputs. The model inputs and intermediate outputs have been checked against the results reported by others including Wang (1999), Delucchi (1998) and Shapouri (1995) for similar analyses done for other areas.

This chapter develops the technical basis for the fuel cycle modeling analysis conducted for the study and reported in Chapter 5. The chapter is organized to provide a discussion of background information and a basis for the assumptions made for the analysis in this study for corn production, ethanol and DDGS production from corn, and the use of ethanol blends in on-road vehicles.

3.2 Corn Farming

Corn is Canada's third largest grain crop after wheat and barley. It is the most important grain crop in Eastern Canada and over 70% of Canada's corn is grown in Ontario. Canada's total annual production is about seven million tonnes of corn grown on about one million hectares. Corn is used as livestock feed, as well as for production of a variety of food and industrial products. Corn is also an important feedstock for fuel ethanol production throughout North America.

The projected supply and disposition of Ontario corn for the 1998/99 crop year is shown in Table 3-1. (www.ontariocorn.org/supply.html). Agriculture and Agri-Food Canada reported that thirty seven percent of the reported corn feed usage in the 1995/96 crop year was for beef and dairy cattle (AAFC Bi-weekly Bulletin). This is an important number, since some of it can be replaced with the DDGS from ethanol production, which has potential implications on GHG emissions, as discussed later. Soybean meal is another important animal feed ingredient that can also be replaced with DDGS.

Table 3-1 Production and Disposition of Ontario Corn 1998/99

	1,000 tonnes	1,000,000 Bushels
Production	6,044	238
Food and Industrial use	1,829	72
Feed use	3,708	146
Exports less Imports	508	20

3.2.1 Farming Practices

Ontario corn production has undergone many changes over the past forty years. With the development of better yielding and earlier maturing hybrids', corn acreage expanded rapidly during the 1960's and the 1970's. By 1980 over one million hectares of cultivated farmland was seeded annually to corn. On many farms corn became the only crop grown. By the late 1970's it was apparent that monoculture corn was causing several economic and environmental problems. Soils seeded to corn year after year, especially with the intensive tillage methods dominant at that time, were becoming poorer in soil structure and more prone to soil erosion. Corn yields on many farms were stagnant despite the release and usage of a steady stream of new hybrids of increasing yield potential. The production of only one crop meant excessive instability in farm income. Corn rootworm, an insect pest in monoculture corn became prevalent across Ontario and this necessitated the application of soil insecticides where corn was grown for two years or more in succession. As a result of the above corn was perceived, with some justification, to cause farm environmental problems.

Major improvements to corn farming have been implemented since the 1980's. Corn acreage began to decline and is now 20% lower than at its peak in the 1980's. Crop rotations and conservation, or no-tillage practices have replaced monoculture cultivation and the intensive tillage practices. Pesticide and herbicide application rates have declined and residues have become less persistent in the soils. With these changes, corn remains a dominant Ontario crop.

Ontario corn farming practices as they relate to energy consumption have been studied and documented by a number of researchers. Cemcorp (1992) is the most often referenced work in this field. Swanton (1996), Vyn (1994), and Clements (1995) have reported other work in this area.

The work by Cemcorp has been used as the basis for the model inputs, as it is the most detailed and is referenced by some of the other researchers. The Cemcorp data has been updated to account for the increase in conservation tillage over the early 1990's. Hough (1999) estimated that 8-10% of the Ontario corn crop is grown with no-till and 29-35% is grown with conservation tillage. We have used a 40% reduction in field energy applied to 35% of the corn crop compared to the numbers used by Cemcorp. This results in a fuel use of 0.042 USG of diesel fuel per bushel of corn as the model input.

The other major energy use in corn farming is for corn drying. Vyn (1994) estimates that 1704 BTU per litre of ethanol will be used for corn drying in 2000. Cemcorp (1992) estimated 1783 BTU per litre of ethanol and Swanton (1996) reported 1616 BTU per litre. We have used 1700 BTU per litre of ethanol and assumed it was derived half from propane and half from natural gas. The model input is therefore 0.092 USG of propane per bushel of corn and 8.3 SCF of natural gas per bushel of corn.

The energy used in growing can be compared to the US data available in the Delucchi (1998) model. Delucchi's data is based on statistics from the USDA and equates to 20,177 BTU per bushel of corn. Wang (1997) reports 19,176 BTU/bushel based on lower heating value (about 20,900 for higher heating value) and notes that the value is conservative. Our inputs total 23,307 BTU per bushel of corn. The Canadian and USDA data are in different formats, which makes comparison difficult. The increase appears to be primarily related to the amount of energy used for corn drying. We rationalize that the shorter growing season in Ontario compared to the US would result in more drying of the crop required. Ontario has about a 3% lower corn yield than the US, which would also result in higher energy use per bushel produced.

Energy consumption for crop production has been declining significantly over the past twenty years (Swanton 1996, Vyn 1994). The data used here accounts for improvements related to increased yield, and changing tillage practices, but does not account for changes due to increased efficiency of farm equipment from engine, or tractor or implement design improvements during the 1990's. The farming values used are probably conservative, based on comparison with US data, which appears to be more robust, and the age of the Canadian sources.

To model the year 2010 emissions we use the improvement factors built into the Delucchi model. The energy consumption per bushel of corn produced is forecast to decline by 0.3% per year. Swanton (1996) reported energy consumption declined at a rate of 2.5% per year between 1975 and 1991 for Ontario corn production. Based on historical trends, our estimates of future energy usage are conservative.

3.2.2 Corn Yield and Fertilizer Use

Since the early 1950's corn yields have increased at an average rate of 1.5% per year (Tollenaar 1997). Corn yields continue to increase and we have used 116 bushels per acre for a base year of 1996 in the model. For future projections we have factored in an increase in yield of 1.5% per year. This is higher than the 1.0% assumed by Delucchi (1998), but is consistent with the past experience. The introduction of biotechnology for hybrid corn development represents a quantum leap in corn technology and may lead to an acceleration of yield increases, the continuation of past yield growth rates is likely a conservative assumption (Daynard).

Corn has one of the more efficient photosynthetic systems of the major crops in Canada. Significant amounts of fertilizer are required to achieve these high rates of growth. Fertilizers require energy to produce and apply and in the case of nitrogen fertilizers, some of the nitrogen that is applied to the soil is released to the atmosphere in the form of N_2O, a powerful greenhouse gas.

Estimates of fertilizer applications rates were obtained from K. Reid, Nutrient Management Specialist with the Ontario Ministry of Agriculture and Rural Affairs. The nitrogen data is consistent with that published by the Ontario Corn Producers, Delucchi (1998) and Wang (1999). The nitrogen rate is considerably higher than that used by Cemcorp (1992), which was based on fertilizer purchases in 1991. The difference is probably nitrogen that is added to the soil from animal manure. Reid estimates that one third of the nitrogen comes from this source. This nitrogen still contributes to N_2O production, but does not require the same energy to produce as synthetic nitrogen fertilizers do. To account for this in the model we input the full amount of nitrogen applied, but reduce the energy required to produce the fertilizer by one third. The phosphate and potash applications rates are slightly lower than the rates used by Wang and Delucchi, but within the state to state variations in the United States reported by Shapouri (1995). The fertilizer application rates input into the model are shown in Table 3-2.

Table 3-2 Fertilizer Application Rates for Ontario Corn

Fertilizer	Application rate kg/ha	Application rate lb/bu
Nitrogen		
Chemical fertilizer	91.0	0.699
Manure	49.0	0.376
Total	140	1.075
Phosphate	45	0.346
Potash	60	0.461
Lime	0	0
Sulphur	0	0
Sodium Hydroxide	0	0

The rate of conversion of applied nitrogen to N_2O is usually modelled as 1.3% (Delucchi, 1998) or 1.5% (Wang 1999). Agriculture and Agri-Food Canada (1999) reports a range of 0.1% to 1.6% depending on the type of nitrogen fertilizer applied. These results were based on laboratory tests. For the types of nitrogen applied to Ontario corn the weighted average would be 0.65%, assuming manure was on the high side of the range. The impact of reducing this rate from 1.3% to 0.65% is reduction of the greenhouse gas emissions by 3,438 grams CO_2/million BTU of ethanol or about 6%. For modeling purposes, we will use the higher loss rate (1.3%) as it is more accepted in the scientific community. This is an area of uncertainty that can have a significant impact on predicted greenhouse gas emissions and has been investigated in the sensitivity analysis.

Delucchi allows for a carbon storage credit for nitrogen fertilizer that leaves the site as runoff. This nitrogen stimulates aquatic plant growth and stores carbon. It is quite a large factor and effectively offsets half of the N_2O emissions from fertilizer. We have not changed any of Delucchi's inputs in this area.

Pesticide application rates have been declining in Ontario over the past twenty years. The Ontario Ministry of Agriculture, Food and Rural Affairs reports a 16% drop in herbicide use between 1983 and 1993 and a 45% drop in pesticide use per hectare in the same time period (www.ontariocorn.org/env/pest). New data for 1998 is expected shortly. We expect the trend to continue, and are projecting use at 2.7 kg/ha. There have been a number of new products introduced that also require substantially less energy to produce (Vyn, 1994), but we have not included that data in the model since the detail of pesticide use (including amount of the low energy input types used) in 1998 is not yet available. The pesticide use accounts for about 2% of the farming energy before adjusting for the new products. The Ontario pesticide value is about half of that used by Delucchi in his modeling of US emissions.

The total energy required to grow corn can be calculated from the energy used in the planting, fertilizing, spraying, harvesting and drying of the corn, as well as the energy required to manufacture all of the inputs such as fertilizers, herbicides and pesticides. The improved input data for the study area discussed above were combined with the data from Delucchi (1998) to arrive at the fundamental parameters shown in Table 3-3. The use of significant quantities of manure reduces the amount of energy required to grow corn in Ontario.

Table 3-3 Energy Requirements for Growing Corn in Ontario

	BTU/Bushel	BTU/USG Ethanol
Field operations	5,838	2,160
Corn drying	17,056	6,311
Fertilizer	21,360	7,903
Pesticides	998	369
Total	45,252	16,743

Delucchi projects some improvements in fertilizer application rates and energy intensity of fertilizer manufacture over time. The assumptions are shown in Table 3-4. No changes to the Delucchi assumptions have been made for the year 2010 emission projections.

Table 3-4 Rates of Change for Agricultural Chemicals

	Annual rate of Change %
Nitrogen Application per Bushel	-0.5
Phosphorus Application per Bushel	-1.0
Potash Application per Bushel	-1.0
Pesticide Application per Bushel	-0.3
Nitrogen Energy Intensity per Pound	-0.3
Phosphorus Energy Intensity per Pound	-0.3
Potash Energy Intensity per Pound	0.0

3.2.3 Transportation Related Emissions

Corn must be moved from the farm to the ethanol plant. The Chatham plant is located in a major Ontario corn production region. At the present level of production, corn is transported from the farm to the plant by truck over an average distance of 45 miles. This is estimated to result in an energy consumption for transportation of 2,772 BTU/bushel. It is assumed that diesel fuel is used to fuel the trucks.

An expansion of the ethanol industry in Ontario would result in some corn having to be transported a longer distance from the farm to an ethanol plant. This is dealt with in the scale up scenarios later in the report.

3.2.4 Resource Supply and Disposition

One of the most important factors in modeling greenhouse gas emissions from ethanol production is forecasting whether the increased demand for corn will impact on land use and result in changes to the amount of carbon stored either in the soil or in above ground biomass. The standard practice in cases where this is determined to occur is to amortize the change over some period between 15 and 25 years and apply an annual greenhouse gas emission to the crop. Delucchi (1998) details the methodology used in the fuel cycle model and Wang (1999) follows a similar but simpler calculation.

Delucchi (1998) argues that increased demand for corn for ethanol production must result in some new land added to the agricultural base. Where this new land comes from can have a large impact on greenhouse gas emissions. Delucchi assumes that in the US, 5% of the land will come from conversion of forested land, 60% from pasture and range, 20% from other agricultural cropland and 15% from increased yield on existing land. The problem with this argument is that it is not consistent with the historical results over the past twenty years in the US, during which there was a 1,400 million US gallon expansion of fuel-ethanol industry, with only a 1% increase in land devoted to corn. This is illustrated in Table 3-5 with data from the USDA National Agricultural Statistics Service and the US Renewable Fuels Association.

Table 3-5 US Corn and Ethanol Statistics, 1978 and 1998

	1978	1998
Acres harvested, million acres	71,930	72,604
Corn production, million bushels	7,267	9,761
Increase in corn production, million bushels	-	2,494
Fuel ethanol production, million US gal.	0	1,400
Corn used for ethanol, million bushels	0	538

Table 3-5 clearly shows that ethanol production in the US has not caused any significant increase in agricultural land for corn production. The increase in demand for corn has been satisfied by a 33% increase in corn yield. About 22% of the increase in corn supply has been used for ethanol production.

The DDGS co-produced by an ethanol plant are used as cattle feed, displacing corn otherwise used as feed. Based on information from Delucchi, obtained from US experts, the co-product credit for DDGS is calculated from the amount of corn that DDGS replaces in cattle feed rations. Delucchi contends that one pound of DDGS is equivalent to 1.57 lbs. of corn. Consequently, 45% of the corn required for ethanol production in essence is corn diverted from existing use as cattle feed, without having any impact on the cattle industry. This also has the effect of avoiding pressure to increase the land used for corn production. Feed use accounts for about 50% of the total demand for US corn.

Delucchi's assumptions would increase the greenhouse gas emissions from ethanol production in Ontario by 9,005 grams CO_2/million BTU ethanol or 19.7% of our total after accounting for the increased co-product credit from the higher farming emissions. This is equal to 2,070 grams CO_2/bushel of corn.

Wang (1999) took a different approach to estimating land use impacts. He used a USDA simulation model to predict that a 50 million bushel per year increase in corn use for fuel ethanol for 13 years would create a diversion of 97,400 acres from pasture to corn production. The remainder of the corn needs would be met from reducing exports. Corn prices were forecast to rise. It was assumed that importing countries would make up the shortfall by reducing demand (50% of shortfall) due to higher prices and increasing their own production of corn from pastureland for the remainder. Wang's calculations resulted in a net CO_2 emission of 390 grams/bushel of corn. The significant difference in emissions is a direct result of the lack of any assumed conversion of forest land to agricultural land in Wang's calculations.

Wang based his calculations of area required on corn yields of 110 bu/acre (6.9 t/ha). This is high for most importing countries. Tollenaar (1997) reports the land base, yield, and production of corn for major producing countries, as shown in Table 3-6.

Table 3-6 World Grain Corn Production

Country	Area (1,000,000 ha)		Yield			Production (1,000,000 t)	
			(t/ha)		(bu/ac)		
	1984-1994	1995	1984-1994	1995	1995	1984-1994	1995
United States	27.8	27.8	7.26	7.6	121	198.2	198.9
China	20.3	21.3	4.23	4.79	76	86.3	102.0
Brazil	13.4	14.0	2.05	2.36	38	27.5	33.0
Mexico	6.8	7.5	1.96	2.2	35	13.5	16.5
France	1.8	1.7	7.13	7.78	124	12.9	13.0
Former USSR	3.5	3.1	3.14	2.72	43	11.3	8.4
World	129.1	129.9	3.71	3.9	62	479.1	507.0

Two facts are apparent from the table, the first is that world yields are much lower than assumed by Wang, and secondly that there is potential for yields in other parts of the world to increase to those presently achieved in the US. Wang did not factor in the impact of higher prices on efforts to increase yields in other countries, only on the demand for corn. It seems just as likely that higher grain prices would encourage higher use of fertilizers and, thus, cause yields to increase, and/or an increase in the number of acres planted.

To determine what might happen in Ontario we start with the corn that will be displaced from livestock use by the use of DDGS from the corn ethanol plants. Second, we calculate the potential increase in yield over the next ten years and compare these to the increased demand for corn caused by the expansion of the corn ethanol industry from 150 million litres a year to one billion litres per year.

Delucchi (1998) uses a displacement factor for DDGS of 1.57 lbs. of corn per pound of DDGS. Wang (1999) has the DDGS displacement factor based both on corn (1.077 lbs.) and soybean meal (0.823 lbs.). With the lower productivity of soybeans, one acre of corn for ethanol production displaces 1.16 acres of corn and soybeans from current markets (0.3 acres corn and 0.86 acres of soybeans). On this basis no additional land is required but more corn and less soybeans would be grown.

A shift in land use of this magnitude would upset the crop rotation balance and change the supply and disposition of soybean meal in Ontario. The province is a major importer of soybean meal (600,000 to 800,000 tonnes per year, AAFC 1999) and the likely impact would be reduction of demand for soybean in the US. Displacement of the full amount of soybean meal currently imported (700,000 tonnes) would require ethanol production of 1.1 billion litres per year, which. coincidentally is slightly higher than the maximum scenario investigated for this study.

A shift in US soybean production equal to 700,000 tonnes of soymeal is equivalent to 13% of the variation in acreage between the smallest and largest crops in the 1990's. The year to year variations are due to normal changes in supply and demand. On a National basis it appears that the US market could absorb the magnitude of the change contemplated here, however, there may be local impacts that have not been considered for the purposes of this study.

The yield of corn is expected to increase over the next ten years. Continuation of the historical increase of 1.5% per year will increase corn production by 25% by 2010 over the 1996 baseline used for this study. With no increase in acres this will produce 53 million bushels of corn, sufficient to manufacture 535 million litres of ethanol per year.

Considering the increase in corn that could be achieved, together with the additional supply made available from use of DDGS, we conclude that sufficient corn will be available by 2010 to support a one billion litre a year corn ethanol industry. The increased corn yield will provide up to 50% of the corn required, while displacement of corn from animal feeds by the use of DDGS will provide at least 45% of the requirements. Some switching of soybean production to corn production in the United States could also increase the corn supply (up to 75% of requirements). This can be accomplished without converting forest land and pasture land to corn production. Based on this conclusion, we have adjusted the model so that 80% of the corn comes from increased yield and from the displacement of animal feed and 20% comes from switching generic agriculture land (switching from soybeans).

3.2.5 Emissions from Land Use

The cultivation of the soil can have an impact on the fluxes of carbon and methane between the soil and the atmosphere in addition to the nitrous oxide flows that were previously described. Soil organic carbon (SOC) is a function of tillage and residue management systems. Delucchi (1998) assumes that any cultivation results in decreasing SOC levels. He models a reduction of 0.1 kg C/m^2/year, which is at the low end of the range that he reports. Canada has been leading the International effort to better understand the potential role of agricultural soils as carbon sinks. The National Sinks Foundation Paper reports that by the year 2000 Canadian agricultural soils will shift from being a source of carbon to a sink.

The specific situation with soils in Ontario used to produce corn is not as clear as the situation in the Prairies. The Sinks Foundation Paper suggests that Ontario will still be a source of carbon by the year 2010. This conclusion is based on simulation runs of the computer model Century. Rates of change of SOC for crop rotations involving corn for the year 1991 are projected to be a loss of 0.0026 kg C/m^2/year (AAFC 1997). Increases in SOC for continuous corn under fertilization of 0.063 kg C/m^2/year have been reported (AAFC 1999). We have chosen to model a loss of SOC of 0.0026 kg C/m^2/year for the Ontario corn crop. This has a relatively small impact on full cycle emissions from ethanol production, reducing emissions by 655 g CO_2/million BTU of ethanol produced or 1.2% of the total. This is dwarfed by the contribution of the annual growth of above ground biomass from the corn. The model amortizes the above ground growth over a fifteen year period and discounts it an annual rate of 2%. This treatment is unchanged from that of Delucchi.

There are also soil and methane interactions. Overall agricultural soils are a methane sink in Canada (AAFC 1999b), but that is mainly due to well drained uncultivated soils (AAFC 1997b). Well fertilized soils frequently inhibit methane oxidation and are sources of methane. Delucchi models methane emissions as a function of nitrogen applied (0.1 g CH_4/kg N) and as a function of area (25 g CH_4/ha/year). No changes to these parameters have been made.

3.2.6 Energy Use and Greenhouse Gas Emissions for Corn production

The energy use and greenhouse gas emissions can be calculated based on the described inputs and compared to crude oil production. The energy data is shown in Table 3-7 and the greenhouse emissions are shown in Table 3-8. It is interesting to note that corn farming and crude oil production in Canada are quite similar in energy required and greenhouse gases emitted. There are differences caused by the fertilizer production compared to gas leaks and flares.

Table 3-7 Energy Use Comparison Between Crude Oil and Corn

	Crude Oil	Corn
Units	Million BTU used/Million BTU delivered	Million BTU used/Million BTU delivered
Feedstock Recovery	0.1169	0.1002
Fertilizer Manufacture	0	0.0978
Total	0.1169	0.1980

Table 3-8 Greenhouse Gas Comparison Between Crude Oil and Corn

	Crude Oil	Corn
Units	Grams CO_2/Million BTU	Grams CO_2/Million BTU
Feedstock Recovery	8,219	8,912
Gas Leaks and Flares	1,921	0
Fertilizer Manufacture	0	6,654
Total	10,140	15,566

3.3 Basis for the Analysis of Ethanol Production

The CAI plant in Chatham Ontario was used as the basis for modelling the energy efficiency and greenhouse gas emissions associated with ethanol production from corn in Ontario. This plant was constructed and started up in 1997. It is a modern dry milling plant with a name plate capacity of 150 million litres per year.

3.3.1 Production Process Description

The Chatham plant utilizes a continuous cooking and fermentation configuration followed by distillation and dehydration using molecular sieves. The ethanol process is represented in Figure 3-1.

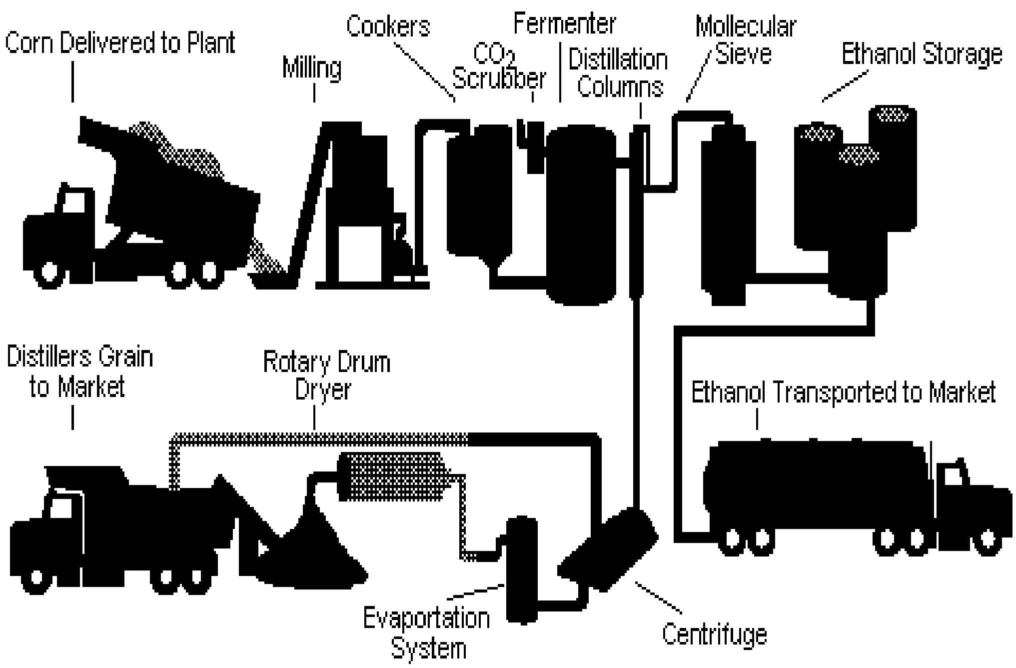

Figure 3-1 Ethanol Production Process

The major steps in the dry milling process are outlined below.

- Milling: The corn first passes through hammer mills, which grind it into a fine powder, called meal.
- Liquefaction: The meal is then mixed with water and the enzyme alpha-amylase, and passes through cookers, where the starch is liquefied. Heat is applied at this stage to enable liquefaction. Continuous cookers with a high temperature stage (120-150 º C) and a lower temperature holding period (95 º C) are used.
- Saccharification: The mash from the cookers is cooled and the secondary enzyme (gluco-amylase) is added to convert the liquefied starch to fermentable sugars, a process called saccharification.
- Fermentation: Yeast is added to the mash to ferment the sugars to ethanol and carbon dioxide. Using a continuous process, the fermenting mash is allowed to flow, or cascade, through several fermenters, until the mash leaving the final tank is fully fermented.
- Distillation: The fermented mash, now called "beer", contains about 11% ethanol by volume as well as the non-fermentable solids from the corn and the yeast cells. The beer mash is pumped to a continuous flow, multi-column distillation system, where the ethanol is separated from the solids and water. The ethanol leaves the top of the final column at about 96% strength, and the residual mash, called stillage, is recovered from the base of the column and transferred to the co-product processing area.
- Dehydration: The ethanol from the top of the column passes through a patented dehydration system, where the remaining water is removed. The alcohol product at this stage is called anhydrous (pure) ethanol.

- Co-product recovery: Evaporators and gas fired rotary dryers are used to remove the water from the stillage and produce DDGS.

The plant is capable of making high purity industrial ethanol as well as fuel ethanol. The industrial alcohol section of the plant contains additional distillation columns and molecular sieves. There is substantial extra energy required to produce the industrial ethanol. For the purposes of the analysis for energy efficiency and greenhouse gas emissions, the industrial alcohol section of the plant was ignored. Energy in the form of steam and electricity used in this section was removed from the total energy used at the plant. Corrections were also made to the electrical energy requirements of the cooling water system.

The Chatham plant also collects and liquefies carbon dioxide produced at a high concentration from the fermenters as a by-product of the fermentation process. This product is a saleable commodity. The energy required for this processing was determined separately so that it could be evaluated as a co-product. This is discussed further in section 3.3.3.2.

The plant derives its thermal energy from the use of natural gas in steam boilers. One boiler is a waste heat boiler capturing the heat from a gas-fired turbine that is used to produce a portion of the plants electrical requirements. Additional electricity required by the plant is purchased from the utility.

3.3.2 Energy Use and Greenhouse Gas Emissions

The ethanol plant data has been corrected for the carbon dioxide capture and the production of industrial ethanol. The variables used in the model are shown below in Table 3-9.

Table 3-9 Ethanol Plant Data Used for Modeling

Parameter	Value	
Ethanol yield	400 litres/tonne corn	2.69 US gal/bu
DDGS yield (dry)	286 kg/tonne corn	16 lb/bu
Natural gas consumed	13.49 MJ/l	48.37 SCF/US gal.
Electricity purchased	0.074 kW/l	0.279 kW/US gal.
Diesel fuel consumed	0.000115 l/l ethanol	0.000115 USG/US gal. ethanol
Chemicals consumed		
Caustic soda	0.045 kg/l	0.078 lb/US gal.
Sulphuric acid	0.047 kg/l	0.08 lb/US gal.
Ammonia	0.027 kg/l	0.046 lb/US gal.

Source CAI.

The corn used at the plant is assumed to arrive by truck. The ethanol leaves the plant by truck. The average distance to the point of blending is 140 miles. The DDGS leaves the plant by truck and by rail. The Delucchi model being used does not model this movement as rigorously as the inputs; it is accounted for as a ratio of the distance that the corn travels to come into the plant. We have used a factor of 6.7 to account for the combined truck and rail movement of DDG. It was assumed that all material is dried and no product is shipped wet. All truck movements are assumed to use diesel fuel.

Table 3-10 shows the greenhouse gas emissions for the production of ethanol compared to gasoline for the manufacturing portion of the lifecycle.

Table 3-10 Greenhouse Gas Emissions for Fuel Production Only in 2000

	Gasoline	Ethanol
Units	grams CO_2 equivalent/ million BTU	grams CO_2 equivalent/ million BTU
Fuel Dispensing	160	165
Fuel Distribution and Storage	774	1,534
Fuel production	8,755	38,927
Feedstock transmission	371	1,588
Total	10,060	42,214

Table 3.11 shows the energy consumed by the ethanol process compared to gasoline for the process steps identified above. The co-product credits have not been accounted for in this table.

Table 3-11 Energy Consumption for Fuel Production Only

	Gasoline	Ethanol
Energy used in production process/ million BTU produced	118,100 BTU	623,500 BTU
Energy used in production step only/US Gal	14,762 BTU	53,040 BTU

3.3.3 Co-Products and Displaced Emissions

3.3.3.1 Distillers Dried Grains with Solubles

Dry mill ethanol plants such as the Chatham plant produce approximately equal weights of ethanol, DDGS, and carbon dioxide. Carbon dioxide is collected from the fermentation stage, cleaned and compressed before it is sold. The DDGS is recovered after distillation, then dried for sale as an animal feed ingredient.

The treatment of the energy consumption and the greenhouse gas emissions imbedded in the co-products can be handled several different ways. The four methods that have been used in past studies (Wang 1999) are:

- Product Displacement
- Market value
- Energy content
- Weight proportions

The most recent works in the field have used the product displacement method (Wang 1999 and Delucchi 1998). The displacement method attempts to model a world with and without ethanol production. It is a more realistic representation than arbitrarily assigning co-product credits based on monetary value, weight or energy content. The displacement value is used here. It should be noted that the displacement method generally gives the lowest values for co-product credits.

Selecting the method of co-product credit is only the beginning; determining what is displaced is also critically important. Early work assumed that DDGS replaced soymeal as a protein source (Marland and Turhollow 1991). This analysis was done strictly on the basis of protein content and ignored any impact that the different types of protein might have in animals' rations. The authors acknowledged the simplicity of their approach. Ruminants at some stages of development require that the protein be available in the intestine (by-pass protein), DDGS has a high percentage of its protein available as bypass protein whereas soymeal does not. To overcome this deficiency it is important to know how the material interacts with the animal.

Delucchi (1998) assumes that the DDGS is used to feed cattle in a feedlot and that 1.57 pounds of corn are displaced by one pound of DDGS. This displacement factor is similar to that which can be calculated from the work of Trenkle (1996 and 1997) Klopfenstein (1994 and 1999) and experienced by Pound Maker Agventures Ltd. at their Saskatchewan ethanol plant feedlot complex, although they have wheat distillers grains replacing barley. The research work highlights the fact that higher values can be attributed to DDGS for smaller younger cattle than for more mature cattle near their slaughter weight. The 1.57 factor is appropriate over the complete feedlot growing cycle.

The problem with this approach is that not all of the DDGS is used as cattle feed in a feedlot. A large portion of the DDGS from the Chatham plant is being used in the dairy market where there is a large demand for bypass protein and it is well established that materials such as DDGS will increase milk production. CAI reports that 30% of their production is displacing soybean meal and the remainder is competing in traditional DDGS markets. Wang (1999) reports that a meeting of feed experts held at Argonne National Laboratory determined that the appropriate displacement ratios for DDGS were 1.077 lbs. corn and 0.823 lbs. of soybean meal. Participants at this meeting included Delucchi, Trenkle, Klopfenstein and others who had supplied Delucchi with some of his original data.

The model used to make the calculations of energy consumed and greenhouse gases emitted is also capable of calculating those factors for soy methyl ester (biodiesel or SME) and that data can be used to calculate the emissions displaced from soybean meal. We have used Delucchi's data for soybean and SME because it is likely that we are displacing US imports of soymeal and the production data for Canada is likely to be very close based on the comparison of corn data. The emissions produced during the farming of corn and soybeans are compared in Table 3-12.

Table 3-12 Greenhouse Gas Emissions for Growing Corn and Soybeans

	Corn	Soybeans
Units	grams CO_2/bushel	grams CO_2/bushel
Feedstock transmission	363	476
Farming	2,037	5,059
Land use and cultivation	208	-165
Fertilizer manufacture	1,521	899
Total	4,129	6,269
Total grams CO_2/lb.	73.7	104.5

The greenhouse gas emissions from the processing of soybeans was reported at 3,645 grams CO_2/ bushel by Marland (1991) and 7,200 grams CO_2/ bushel by Delucchi (1998). Allocating the emissions by weight between the oil and meal and using Marland's value the emissions displaced for soybean meal are 9,914 grams CO_2/bushel of soymeal (6269 +3645). This is 165.2 grams CO_2/lb. The two methods for co-product displacement are compared in Table 3.13.

Table 3-13 Greenhouse Gas Credits for DDGS Co-Products

	Delucchi	Wang
One pound DDG equals	1.57 pounds of corn	1.077 lbs. corn +0.822 lbs. Soybean meal
	1.57*73.7=115.7	1.077*73.7 +0.822*165.2=215.2
CO_2 emissions /lb DDG	115.7 grams	215.2 grams
DDG production/million BTU ethanol	70.4 lbs.	70.4 lbs
CO_2 emissions per million BTU ethanol	8,145	15,148
Less transportation	2,693	2,693
Net credit	5,452	12,786

It can be seen that the inclusion of the displacement of soybean meal by DDGS produces a much higher credit than only using corn as the displaced material. This is due to the lower productivity of producing soybeans (a much lower yield) and the energy expended by the processing of the beans into the high protein meal.

Delucchi also models the credit on the basis of a proportion of the energy consumed in the lifecycle. Fifteen percent is the proportion that he uses and that results in a net credit of 5,911 grams CO_2/million BTU ethanol.

Throughout the report the credit will be based on the displacement factors reported by Wang. These are the most representative of the use of the DDGS generated by the Chatham plant and the livestock industry in Ontario, Quebec and the North East US.

3.3.3.2 Carbon Dioxide

The ethanol process produces carbon dioxide (CO_2) as it makes ethanol. The Chatham plant has the capacity to produce 120 kt/year of carbon dioxide for the merchant market in Ontario, Quebec and the Eastern United States. The total Canadian merchant market demand is 800 kt/year. Captive demand for CO_2 is more than 2.5 million t/year, primarily for urea production at plants in Western Canada.

Ethanol plants, oil refineries and power plants supply the merchant market for carbon dioxide. The concentration of carbon dioxide will be highest at the ethanol plant and lowest when the CO_2 is extracted from the exhaust gases of a power plant. The more concentrated the CO_2 the less energy will be required to concentrate and purify it. It could be argued that CO_2 from an ethanol plant would cause less efficient CO_2 producers to leave the market and thus a co-product credit equivalent to the difference in energy consumed between and ethanol plant and a power plant should be applied. The energy consumed is mostly electricity and in Ontario the electricity is mostly from non carbon sources so any benefit in greenhouse gas is small. The energy used by CAI is 0.523 kWh/USG of ethanol. If this was 0.28 kWh less than an alternative CO_2 source the total GHG emissions from the ethanol plant would be reduced by 0.4%. Due to uncertainty of displacing other sources of CO_2 and the small credit available we have not included this as a co-product credit.

3.4 EFFECTS OF ETHANOL BLENDS ON MOTOR VEHICLE EMISSIONS

3.4.1 Vehicle Fuel Economy

Ethanol is an oxygenated compound. As such it contains less energy than gasoline components that do not contain oxygen. Ethanol has about 67% of the energy of gasoline per unit volume. Blends of ethanol and gasoline have a poorer fuel economy on a volumetric basis since the fuel contains less energy. This lower fuel economy has been demonstrated in a number of laboratory studies. However the magnitude of the change is less than predicted by the change in energy content.

The Auto/Oil Air Quality Improvement Research Program (Hochauser 1993) of the early 1990's reported that the current vehicle fleet (1989 vehicles with emission control systems similar to today's vehicles) achieved a 1% better energy specific fuel economy when 10% ethanol was added to gasoline. Ethanol blends were not tested in the older fleet, but methyl tertiary butyl ether (MTBE) was tested, and it was found that better energy specific fuel economy was found in the older fleet than in the current fleet.

Ethanol has a higher heat of vapourization, a higher specific energy ratio and produces more moles of combustion products per mole of combustion air than gasoline (Owen 1990). These three chemical characteristics probably account for the higher energy efficiency of ethanol blended gasoline. For low level blends of less than 10% we have scaled the energy specific fuel consumption in proportion to the ethanol content based on the results from the Auto/Oil study. For the 85% blends Wang (1999) reports a 5% better energy specific fuel economy and that is modelled.

3.4.2 Greenhouse Gas Emissions

To model the greenhouse gas emissions appropriately it is necessary to know the vehicle fuel economy. The primary reference for this data was Canada's Energy Outlook 1996-2020 (NRCan, 1997). The fuel economy data was disaggregated into city and highway on-road fuel economies that are the key parameters used in the fuel cycle model.

On road fuel economy of 9.6 l/100 km for 2000 and 9.0 l/100 km for 2010 were used for light duty automobiles. The 2010 values assume that no changes in Corporate Average Fuel Economy Standards are introduced.

The analysis of fuel cycle emissions utilizes annual distance travelled and vehicle survival statistics to estimate cumulative distance travelled of a typical vehicle and its non-greenhouse gas emissions at the mid-point of its life. The annual kilometer accumulation rates and survival fractions used in this study for passenger cars and heavy-duty vehicles were provided by NRCan for Alternative and Future Fuels and Energy Sources for Road Vehicles (Levelton, 1999).

3.4.3 Non-Greenhouse Gas Emissions

Ethanol blended gasoline can reduce exhaust emissions of carbon monoxide and hydrocarbons. Emissions of nitrogen oxides are dependent on the fuel characteristics and how the ethanol is blended. If ethanol is used to replace other high octane components such as olefins and aromatics NO_x can be reduced. NO_x can increase slightly when the ethanol is splash blended which is not the case assumed here. Changes in non-greenhouse gases are proportional to the oxygen content of the fuel for low-level blends. For modelling purpose we have assumed that the only change to exhaust emissions is a reduction in carbon monoxide and a reduction in non-methane hydrocarbon emissions with the ethanol blends. All other emissions stay the same, including evaporative emissions because we are assuming that the ethanol is incorporated into the refinery blending system and the fuel meets the appropriate vapour pressure specifications. The impact of these changes is to increase emissions of CO_2 since more of the carbon in the fuel is converted to carbon dioxide rather than carbon monoxide.

In preparation for an update to the EPA Mobile model the effect of fuel oxygen content on CO emissions has been prepared by the US EPA (Rao, 1999), it was concluded that Tier 0 "normal-emitter" vehicles (US model years 1982-1994) emit 4.5% less CO for each 1 weight percent increase in oxygen in the fuel. For high-emitting vehicles, CO is reduced 5.3% for each 1 weight percent increase in fuel oxygen content. The reduction in CO emissions has been found from tests of vehicles of different ages and that were equipped with different catalytic control technology to range from about -10.9% to -32.9% for a blend of 10% ethanol in gasoline (3.5 wt% oxygen).

Rao (1999) also reports that oxygenates such as ethanol causes only a very small reduction in CO emissions for Tier 1 vehicles (post 1994 model year). Paired tests of vehicles using gasoline without oxygen and gasoline containing 2 wt% oxygen found only a 1% decrease in CO emissions. Tests with advanced low-emission vehicles (LEV) found that CO emissions increased slightly with addition of an oxygenate to gasoline. Based on these results, the US EPA is assuming that oxygenates will have no significant effect on CO emissions from Tier 1 and LEV vehicles.

We have assumed that the reduction in CO emissions for 2000 and 2010 vehicle fleets is 10%, based on the observed vehicle test results.

The EPA is not planning on updating the VOC emission factors in the Mobile model. The non-methane hydrocarbon emission reduction projected by Mobile 5C model is between 9 and 13% for a 10% ethanol blend. To be conservative we have modeled a 9% reduction.

The emission reductions that we have modelled are less than those predicted by Environment Canada's Mobile 5C model; however the US EPA's new version, Mobile 6 has a much lower reduction for carbon monoxide than the earlier versions. The reduction of hydrocarbon emissions in new vehicles is lower than for the older fleet and will continue to drop as the newer, cleaner vehicles replace old vehicles in the fleet.

E85 vehicles are designed to meet the same emission standards as their gasoline counterparts. Current E85 vehicles are designed to be fuel flexible and thus meet emissions standards for both gasoline and ethanol. It is difficult to reach any conclusions regarding fuel impacts on non-greenhouse gas emissions from these vehicles.

3.5 Other Considerations and Assumptions

The CAI plant has experienced a number of difficulties during its start up phase. Most of the problems have been related to the co-product drying section of the plant. These problems have impeded the ability of the plant operators to run the facility at a steady state and to determine the optimum operating conditions. This has an impact on the energy consumption in the plant. Based on experience with other ethanol plants in Canada and published data from US plants it is expected that the CAI plant will be able to reduce their consumption of natural gas at the plant by at least 15 to 20% through operational changes alone. This would reduce the energy required from 50,703 to 43,907 - 40,560 BTU/US gal. Wang (1997) surveyed the literature and reports energy use for US corn dry milling operations between 36,700 BTU/US gal and 53,260 BTU/US gal based on lower heating values.

Our estimate of the potential for the Chatham plant is thus within the range of existing plant experience. For the scenarios modelled in the year 2010 we will use Wang's lower number corrected to a higher heating value of 40,000 BTU/US gal for energy consumed in the plant. This represents an annual improvement of 2.3%. Delucchi models an annual improvement factor of between 0.3 and 0.4% depending on the split between coal and natural gas used to generate the steam. A higher rate is appropriate for Canada given the lack of maturity of the industry in Canada compared to the US. The American industry has had up to twenty years to improve the energy efficiency of some plants and the easy tasks have been done.

3.6 SUMMARY OF ETHANOL PRODUCTION AND USE

The farming, processing and co-product energy consumption data from this and a number of recent studies is summarized in Table 3-14. The data has all been converted to a higher heating value basis for comparison. The use of manure for a portion of the nitrogen requirement is the reason for lower energy use in producing corn in spite of higher on farm energy use. The co-product credits for this study are based on the displacement method so lower farm energy use lowers the value of the credit also.

Table 3-14 Energy Consumption Comparison (BTU/US Gallon Ethanol)

Study	Farming	Processing	Co-Product Credit		Total	Net
				Method		
This Study	17,775	50,415	14,055[1]	Displacement	68,190	54,135
Wang (1997)	21,200	45,540	20,120	Energy Allocation	66,740	46,620
Shapouri (1995)	29,547	53,277	15,056	Market value	82,824	67,768
ILSR (1992) Average	20,088	51,695	27,579	Market value	71,783	44,204
ILSR (1992) Best	12,998	33,839	36,261	Market value	46,837	10,576

[1] Does not include transportation to market.

4. Gasoline Production and Effects of Ethanol Blending

4.1 Gasoline Production and Supply in Southern Ontario

The Ontario petroleum refining industry has gone through dramatic changes over the past 25 years. Today, the production facilities consist of five refineries producing transportation fuels with some additional crude processing capability at Novacor in Sarnia, which produces chemicals. Total crude processing capacity in Ontario is approximately 500,000 barrels per calendar day. At present the industry is operating at about 90% crude capacity, however, in most cases secondary units are being run full.

Feedstock for Ontario refineries has traditionally come from Western Canadian crude oils, synthetics and bitumens. Some capability exists to import crude from the USA through Chicago based pipelining networks, but this has not generally proven economically feasible. Normally crude movements have been into the United States along with surplus propane, butanes and condensates. Starting in May 1999 the Sarnia-Montreal IPL pipeline has been reversed, opening up the import capabilities of offshore crude from world producers.

During the past 25 years, world crude oil crises have resulted in most major US refiners investing heavily in metallurgy and hardware to allow the processing of cheaper, heavier and sour crude oils. This has not been the case in Canada and in particular in Ontario. With the exception of Imperial Oil at Sarnia, Ontario refineries are still dependent mainly on light sweet crude oil. This dependency will increase as regulations for lower sulphur in gasoline and diesel fuels come into effect.

Although the Ontario refineries may be considered rather small and dependent on sweet crude oils, the petroleum refining industry has kept up to date with advanced computer control technology as well as modernization of their facilities. As a result, the industry is among the most efficient in the world and possesses excellent skills for optimizing feedstocks, blending components and quality requirements. Furthermore, the industry has an excellent distribution system throughout the province that consists of modern "state-of-the-art" pipeline networks linking all major centres within the golden horseshoe corridor from Sarnia to Montreal including a lateral to serve Ottawa. Along with modern product loading facilities and fuel efficient truck fleets, the distribution of products in Ontario is as efficient as any in the world.

The marketing of gasoline in Ontario has also undergone a major metamorphosis in recent years. Gone are thousands of small and often less efficient service stations. Today the emphasis is on large major service stations that offer many additional customer services like car washes, quick food outlets and basic corner-store items. In most cases these facilities are company owned and operated.

For this review, only the five complete refineries will be considered and a more in-depth discussion follows this brief overview. While information is provided on each refinery an aggregate of the data has been prepared to represent the Ontario refining industry. Modeling in this study has been done with the aggregate data that is representative of the Ontario industry, but does not apply to any specific refinery or company.

4.2 Description of Refineries, their Current Configuration and Effects of Fuel Sulphur Regulations

4.2.1 Petro-Canada, Oakville

The Petro-Canada Refinery in Oakville has a rated capacity of 85,000 barrels per stream day. The effective capacity used in this review is 80,500 barrels per calendar day. The original plant, built in 1958 was expanded in 1974 by mirror-imaging the Atmospheric Crude Unit, Fluid Catalytic Cracking Unit (FCCU) and Catalytic Reforming Unit along with necessary auxiliaries. Presently, the plant processes crude through parallel crude trains. The older crude unit operates basically on heavy sour asphaltic crude oils to meet a high asphalt demand. The newer crude unit processes light sweet crude to produce the usual components as well as lube oil feedstocks for the Petro-Canada Mississauga Lube Oil facility. The Mississauga Refinery is partially integrated with the Oakville Refinery. Besides producing at least part of Mississauga lube feedstock requirement, naphtha from Oakville is also moved to the Mississauga facility for reforming through their 10,000 bbls./d. Catalytic Reforming Unit.

The Oakville Refinery is a basic plant with small duplicated units however it has a reputation for excellent maintenance and high efficiency on-stream times. The refinery is presently engaged in construction and startup of an Isomerization Unit that should increase gasoline pool R+M/2 octane capability.

4.2.2 Imperial Oil, Sarnia

This is Ontario's largest refinery rated at 126,000 barrels per stream day with an effective rating of 119,000 barrels per calendar day. The refinery is a highly complex plant that has a substantial gas-oil cracking capacity (47%), and is the only refinery in Ontario that has true bottoms upgrading capabilities. The refinery's Fluid Coking unit is a thermal cracking process utilizing fluidized-solids technique to remove carbon (coke) from continuous conversion of heavy, low-grade oils into lighter products. The refinery burns the coke produced as fuel. Over the years, a residuum-based stream from Imperial Oil's Strathcona, Alberta refinery has been processed here. Thus Imperial's Sarnia is equipped with an effective triad of FCCU, Hydrocracking Unit (HCU) and Coker, making it Ontario's lowest cost producer. As well, over past years Imperial has invested time and money at Sarnia to make the refinery one of North America's most energy efficient facilities, thus adding further to its cost competitiveness.

The refinery has both lube and aromatic facilities and has been integrated with Imperial Oil’s Nanticoke refinery to optimize operations at both plants. With ample reforming, catalytic cracking and alkylate capacity within the integrated complex, Imperial should have no difficulty meeting new gasoline specifications other than sulphur in both gasoline and diesels.

4.2.3 Imperial Oil, Nanticoke

The Nanticoke Refinery was built in 1978 by Texaco and is Ontario's newest refinery. The refinery has an effective capacity of 112,000 barrels per calendar day. Originally designed as a major gasoline producer, the plant was upgraded in the late 1980's and early 1990's. Today it is an efficient fuels refinery with an improved FCCU, a continuous regenerating reformer and modern computerized operation and control.

Nevertheless, Nanticoke is still a basic fuels refinery that by and large is limited to sweet light crude although some light sour can also be processed now that the refinery has distillate desulphurizing capabilities. As well, integration with Imperial Oil's Sarnia refinery should provide opportunities to alleviate some constraints on the refinery.

Although Nanticoke has excellent octane generating capability the plant may face problems with future gasoline sulphur specifications.

4.2.4 Shell Canada, Corunna

The Shell refinery at Corunna is rated at 80,400 barrels per stream day with an effective rating of 71,400 per calendar day. The plant processes light sweet and sour crude oil with occasional small amounts of heavy sour crude.

The refinery was originally build in 1952 and has been upgraded on a number of occasions. It has both a FCCU and a HCU as well as a small Viscbreaker. It produces aromatics in support of an associated petrochemical complex. The plant is limited on sulphur removal and will experience problems meeting future octane requirements.

4.2.5 Sunoco, Sarnia

The Sunoco Refinery at Sarnia is rated 85,000 barrels per stream day, but in this review it is given an effective rating of 70,000 barrels per calendar day. The Refinery has been updated and modernized and possesses "leading-edge" computerized control technology with on-line optimization of yield and energy value applications making it a very efficient and profit oriented operation. The refinery possesses the highest gas-oil cracking percentage (64%) in the province as well as ample octane capabilities with a large reformer and an adequate hydrofluoric acid Alkylation Unit. Although the effective capacity appears low compared to rated capacity, the refinery strives to operate all secondary units at capacity by processing mainly synthetic crude (no bottoms) and by purchases of feedstocks from other Sarnia chemical operations.

The refinery has BTX (benzene, toluene, xylene) facilities and produces aromatics, both for domestic and export markets. Like all Ontario refineries, Sunoco receives crude oil by pipeline and ships most of their products through their jointly owned pipeline network to London and Toronto terminals for distribution to their Ontario markets. Like all five Ontario refineries, Sunoco is accessible to the Great Lakes and the St. Lawrence Seaway System through their own dock and product loading facilities.

Sunoco is the only Ontario refiner who is presently blending 6-8% by volume of ethanol into their gasoline pool. They purchase all of CAI's fuel ethanol production from Chatham Ontario. The ethanol is blended into gasoline at Sunoco terminals in London, Toronto, and Sarnia.

Sunoco has ample octane and would have no problem meeting new gasoline specifications even without ethanol. Sunoco currently has the lowest gasoline sulphur level in the province. They will require upgrading to meet the 30 ppm sulphur gasoline standard in 2005.

4.2.6 Fuel Sulphur Regulations

The Federal Government has introduced new lower limits on sulphur in gasoline. The regulations will be phased in between 2002 and 2005. By 2005 the average sulphur content of gasoline must be less than 30 ppm. This is a significant reduction from the current Ontario average of about 500 ppm. Refiners have a number of processing options available to them to meet the new standards. All of the options require extra energy to be expended in the refinery. The energy is used to remove the sulphur from the refinery streams and to replace some gasoline octane that is lost in the sulphur removal process.

The CPPI (Purvin & Gertz, 1999) has estimated the energy required to meet the new regulations will be about 3,500 BTU/US gal. This assumed that existing technology is used to remove the sulphur. The US EPA took the approach that new technologies will be used that are more energy efficient and used a value of about 2,000 BTU/US gal. The EPA (1999) also looked at the technology considered by the CPPI and arrived at a similar number to the CPPI. We took a bottom up approach to each of the process units involved and arrived at a value of 2,900 BTU/US gal of gasoline. We calculated 1,200 BTU/US gal to make up for the loss of octane and 1,700 BTU/US gal for the desulphurization. This value of 2,900 BTU/US gal is used for the extra energy in the base year and the normal refinery energy efficiency improvement rates are applied to it as well so that by the year 2010 it is expected that the energy required will be only 2,580 BTU/US gal.

The more energy efficient technologies are not considered likely for most Ontario refineries because the Canadian regulations will require investments to be made before 2002 and the technologies will not be proven soon enough to allow them to be installed prior to the first stage of the regulation taking effect. Only one of the Ontario refineries can meet the 2002 standard today without any investment and is a potential candidate for the new technologies.

The low sulphur gasoline does have a number of positive impacts on greenhouse and non-greenhouse gas emissions. The US EPA (1998b) expects the emission rate for N_2O to be about 60% lower with the lower sulphur fuel. Emissions of non-greenhouse gases are expected to be 11-16% lower with the low sulphur gasoline for Tier 1 vehicles (EPA 1998). These reductions are incorporated in the model for the 2010 cases.

4.2.7 Typical Refinery and Crude Oil Inputs

The typical Ontario refinery has a capacity of 90,000-bbls/calendar day. It is running at 90% of capacity. The refinery has the capability of adjusting its gasoline output from 44% to 50% of capacity. The crude oil slate is mostly light sweet crude oil but some synthetic, heavy and bitumen is processed. The crude oil slate is shown in Table 4.1.

Table 4-1 Typical Crude Oil Slate for Southern Ontario

Crude Oil Type	Percent of Input
Light Sweet	63
Heavy	18
Synthetic	12
Bitumen	7

It is assumed that the crude oil is produced in Western Canada and shipped by pipeline to the refineries. It is recognized that some of the crude oil now being supplied to these plants is offshore oil, but it is considered reasonable that offshore oil has a similar quantity of greenhouse emissions as estimated for Canadian crude oil.

The greenhouse gas emissions associated with the production of the crude oil is derived from the foundation paper for the upstream petroleum sector presented to the Industry Table of the

National Climate Change Process (CAPP, 1998). The CAPP data was disaggregated by crude oil type and then combined in the same proportions as that used by the typical Ontario refinery. The numbers will be different than the Canadian average production because of this. The crude oil slate used here produces lower greenhouse gas emissions than the national average crude oil slate. The greenhouse gas emissions for the extraction of crude oil and the movement from Alberta to the Ontario refineries is shown in Table 4-2. The equivalent corn farming numbers are shown for comparison.

Table 4-2 Greenhouse Gas Emissions for Crude Oil and Corn Production

	Oil Production	Corn Farming
Units	gram CO_2 eq/million BTU	Gram CO_2 eq/million BTU
Feedstock Recovery	8,219	8,912
Feedstock Transmission	371	1,588
Gas Leaks and Flares	1,921	0
Fertilizer Manufacture		6,654
Total	10,510	17,154

4.3 Refinery Energy Use for Conventional Gasoline and Ethanol Blends

The energy consumed in the refinery for gasoline production has been calculated for our typical refinery on a ground up, unit by unit basis. The total was then compared to the national average energy consumption as published by the Canadian Industry Energy End-use Data and Analysis Centre (Nyboer). The results compared very favourably and we have used our calculations for the total energy input into the model and CIEEDAC data for guidance on the proportion of each type of energy source that makes up the total. All Ontario activities benefit from the low carbon intensity of electric power generation in Ontario although this benefit will decline as more coal is projected to be used for electricity generation in future years.

The total energy used in the refinery is allocated to the various products produced on the basis of the energy actually used in each step. Products such as gasoline that go through multiple processes are assigned more energy than a heavy distillate that might only see one process step. This allocation of co-product credits is not the same approach used in the ethanol plant but it is consistent with approaches taken by others (Wang, 1999 and Delucchi, 1998).

The energy used to produce the gasoline in our typical refinery is 13,530 BTU/US gal for a base year of 1998. This has been adjusted to 14,090 for the model base year of 1996. It is recognized that refineries are reducing their energy inputs and we have reduced the energy consumption by 1% per year until 2001 and 0.5% per year after that until 2010. Delucchi does not take this systematic approach to energy efficiency in the refinery unlike most of the other fuel production processes that he models. This approach was also taken in the Canadian version of the model (Levelton, 1999).

The energy input is for the maximum gasoline production rate, which is the most efficient, with some spare distillate capacity and an overall 90% crude capacity level. Ethanol not only replaces gasoline volume but it also adds octane to the gasoline pool. To take advantage of this octane a refinery has several options:

- Remove and sell other high octane material such as the aromatics benzene, toluene and xylene,

- Reduce the operating severity of the reformer, which is usually the refinery's lowest cost source of incremental octane,
- Increase gasoline production,
- Some combination of the above.

All of these options should result in lower energy consumption and essentially provides an energy credit to the ethanol. We have modelled the case of lower reformer severity, as there will be a limit to the amount of BTX that the market can absorb. For the base case, where the refineries are not limited by octane, we will give an energy credit of 590 BTU/US gal for a 10% ethanol blend. For the 6 and 8% ethanol blends, the energy credits will be 354 and 472 BTU/US gal respectively.

4.4 Description of Gasoline Distribution Network

The Ontario gasoline distribution system is an efficient network of pipelines, terminals, and truck transport. We have assumed that the gasoline component travels an average of 250 miles by pipeline and 75 miles by truck. The ethanol transportation has been previously described. We are using the model pioneered by Sunoco in Ontario where the ethanol is incorporated into the refinery blending system but is physically blended into the gasoline at one of the major terminals. This overcomes any potential problems with pipeline distribution of ethanol and the ethanol picking up too much water in the process. It is recognized that it is not the most energy efficient means of distributing the final blend.

4.5 Other Issues Associated with Use of Ethanol in Gasoline

The use of ethanol in gasoline increases the vapour pressure of the blend by approximately one-PSI. It has been assumed that the ethanol blends will have the same vapour pressure as gasoline and that the refinery will have to back out butane from the blends to insure that the fuel meets the specifications required. The interaction between ethanol and gasoline is non-linear and will result in the same amount of butane being backed out for a 6% ethanol blend as a 10% blend. If ethanol is used in all of the gasoline produced in the Ontario refineries about 4,100 BPCD[2] of butane will be backed out by the 20,500 BPCD of ethanol added. The butane may represent a challenge to some refineries, as the outlets for it are chemical markets and use as a fuel within the refinery. Neither of these outlets will have the same value as the use as a gasoline component. It may be possible to convert the butane to isobutane for use as alkylation feed but none of the refineries have a butamer unit in place today. Four of the five refineries have alkylation units.

Ethanol is soluble in water and only soluble in gasoline when it is dry so special attention needs to be exercised to keep the distribution system free of water. Ethanol is also a good solvent for some gums and tars that are sometimes found in gasoline systems. Ethanol can loosen these products and cause filters to be overloaded. The use of ethanol by Mohawk and Sunoco in Canada has demonstrated that these problems can be overcome. Ethanol use in the US is about 5.3 billion litres per year producing about 53 billion litres of ethanol blended gasoline, about 50% more than the amount of gasoline sold in Canada each year.

[2] Barrels per calendar day.

5. Full Cycle Greenhouse Gas Emissions for Ethanol Blends and Gasoline

5.1 Ethanol Blends Analyzed and Key Input Assumptions for Cases Studied

A total of four different ethanol blends were analyzed, low-level blends of 6, 8, and 10% and a high-level blend containing 85% ethanol (E85). The low-level blends are capable of being used in all current vehicles interchangeably with existing gasolines. Blends of 6% ethanol have been sold in Ontario by Sunoco for a number of years and 10% ethanol blends have been sold by Mohawk Canada in Northern Ontario and Western Canada since the 1980's. All automobile manufacturers accept gasolines containing up to 10% ethanol. Gasolines that contain more than 10% ethanol may cause excessive enleanment of the air fuel mixture and result in driveability problems. These fuels are not approved by auto manufacturers for use in gasoline powered vehicles. The E85 fuel analyzed is used in vehicles designed to accept high levels of ethanol in gasoline. These flexible fuel vehicles may also operate on 100% gasoline. Ford and DaimlerChrysler currently sell flex fuel vehicles capable of using E85.

The use of ethanol for the production of low-level gasoline blends can be incorporated into the Ontario refineries using the existing flexibility of those facilities. The plants have the flexibility to incorporate as much as 13% ethanol into the gasoline (if they were accepted in the market place) and still meet the requirements of the diesel fuel market. The high octane content of the ethanol will allow some energy savings in the refinery and this has been built into the modelling in the form of reduced refining energy for the low level blend cases.

E85 is sufficiently different to be considered as a new fuel rather than a gasoline blend. Significant quantities of low-level blends and E85 would exceed an individual refinery's flexibility to adjust the gasoline and diesel production ratio. Consequently, the E85 scenarios considered in this study do not allow any energy savings within the refinery.

For the analyses of future years we have followed the improvement rates used by Delucchi (1999) for all assumptions except the energy use in the refinery and the ethanol plant. For the refinery we have assumed that the energy efficiency improves by 1.0% per year until 2001 and by 0.5% per year after that until 2010. This is the same assumption used by Levelton in the original Canadianization of the model and was arrived at through discussion with the Canadian Petroleum Products Institute. Overlaid on this improvement is a specification change for gasoline with the sulphur content dropping to 30 ppm by 2005. This will require a significant increase in energy used in the refinery. For the ethanol plant we have increased the rate of improvement so that by 2010 the plant is as efficient as existing plants in the United States. The improvement rate is 2.3% per year and can be achieved with operating improvements and minimal capital investment. Delucchi is expecting that US plants will achieve a 0.3% improvement from current levels. Our 2010 energy efficiency will thus still be below US levels in 2010.

The improvements that have been modelled do not rely on any technology breakthroughs. They can be achieved through application of known best practices. The improvement rates are modest and in many cases conservative when compared to historical rates of improvement. They could be considered a business as usual case since they do not assume any macro economic changes that would accelerate the adoption of energy conservation practices.

5.2 Full Cycle Energy Balances for 2000 and 2010

Full cycle energy balances for the year 2000 can be calculated based on the data presented in previous sections of the report. The balances are calculated as total energy input to manufacture the product versus the energy contained in the fuel. For the ethanol case the energy output is calculated three ways, the actual energy contained in the fuel, the apparent energy in the fuel based on a 10% blend (1% better energy specific fuel consumption and refinery energy credit) and based on E85 (a 5% better energy specific fuel consumption). The balances are shown in Table 5-1.

Table 5-1 Energy Balances for Year 2000, Gasoline and Ethanol.

	Gasoline	Ethanol
Units	BTU per Million BTU Delivered	BTU per Million BTU Delivered
Energy Inputs: Feedstock Recovery	116,900	100,200
Feedstock Transmission	4,800	12,100
Fuel production	106,000	595,900
Fuel Distribution, Storage and Dispensing	7,300	15,500
Fertilizer	0	97,800
Total Inputs	235,000	821,500
Co-Product Credits	0	156,250[3]
Net Inputs	235,000	665,250
Energy Output	1,000,000	1,000,000
Effective Energy Output, 10% Blends*		1,141,600
Effective Energy Output, 85% Blends*		1,063,000
Net Energy	765,000	334,750
Net Effective Energy 10% Blends**		516,850
Net Effective Energy 85% Blends		397,750

* Based on the energy content of the blended gasoline, allowing for the better energy specific fuel consumption of ethanol. The additional effective energy for a 10% ethanol blend is: 0.01*(120,000 BTU/USgal /(84,750 BTU/USgal *0.10)) = 141,600 BTU/million BTU delivered.

** Includes the refinery energy savings due to ethanol's octane value which equals 90% of 45,000 BTU/million BTU, or 40,500 BTU/million BTU.

The Table shows that producing ethanol in Ontario from corn has a positive energy balance. The ratio of energy output to energy input ranges from a low of 1.50 (1,000,000/665,250) to a high of 1.83 depending on the end use of the ethanol. The ratio of net energy output to energy input for ethanol from corn is substantially lower than that for gasoline. The net effective energy value for 10% blends is 43,800 BTU/US gal of ethanol.

By the year 2010, it is expected that the energy efficiency of the ethanol plants in Ontario will improve to the level of efficient US plants. The trends in farming practices concerning yield and energy use will continue. The refineries will also continue to improve their energy efficiency, but will be producing a lower sulphur gasoline that will require more energy to produce. The impact of these changes is a substantial improvement in the energy balance of ethanol and a small

[3] Includes transportation energy to deliver DDGS to consumer.

decline in the energy balance of gasoline due entirely to the impact of the low sulphur regulation. The results are shown in Table 5-2.

Table 5-2 Energy Balances for Gasoline and Ethanol in 2010

	Gasoline	Ethanol
Units	BTU per Million BTU Delivered	BTU per Million BTU Delivered
Energy Inputs:		
Feedstock Recovery	116,800	95,200
Feedstock Transmission	4,700	11,400
Fuel production	120,700	476,700
Fuel Distribution, Storage and Dispensing	7,100	15,100
Fertilizer	0	88,000
Total Inputs	249,300	686,400
Co-Product Credits	0	136,890[4]
Net Inputs	249,300	549,510
Energy Output	1,000,000	1,000,000
Effective Energy Output, 10% Blends*		1,141,600
Energy Energy Output, 85% Blends*		1,063,000
Net Energy	751,700	450,490
Net Effective Energy 10% Blends*		630,790
Net Effective Energy 85% Blends		513,490

* See Table 5-1 for method of calculation.

For the most energy efficient ethanol case, the net energy produced reaches 84% of that of gasoline after accounting for co-products and the improved energy efficiency of low-level ethanol blends. The range of energy output to energy input is 1.82 to 2.23.

5.3 Full Cycle GHG Emissions of Ethanol Blends and Gasoline

Greenhouse gas emissions of gasoline and ethanol blends were calculated for the fuel cycle. This encompasses the entire life-cycle including oil and corn production, transportation of raw materials and finished products, conversion to automotive fuel, use in the vehicle and emissions associated with the manufacture of the vehicle. The greenhouse gases carbon dioxide, methane and nitrous oxide are included.

5.3.1 Emissions in 2000 and 2010 for 225 million litres/year Production

Emissions for the case of year 2000 and 225 million litres per year of production models the current situation with the ethanol coming from CAI and plants like it. The results can be

[4] Includes transportation energy to move product to consumer.

presented on the basis of the fuel cycle up to the point of delivery to the consumer and on the basis of miles driven. Both presentations add to the understanding of the issue and are presented here. The results are presented in Table 5-3 on the basis of the fuel production cycle.

Table 5-4 presents the predicted greenhouse gas emissions for gasoline and a 10% ethanol blend on the basis of miles driven and including the emissions associated with operation and manufacture of the vehicle. The ethanol is used in the refinery and the octane of the finished blend is the same as gasoline's.

Table 5-3 Greenhouse Gas Emissions for the Production Cycle of Crude Oil and Corn in 2000

	Gasoline	Ethanol*
Units	Grams CO_2 equivalent/million BTU delivered to consumer	Grams CO_2 equivalent/million BTU delivered to consumer
Fuel Dispensing	160	165
Fuel Storage and Distribution	774	1,534
Fuel Production	8,755	38,927
Feedstock Transport	371	1,588
Feedstock Recovery	8,219	8,912
Land Use Changes	0	908
Fertilizer Manufacture	0	6,654
Leaks and Flares	1,921	0
Emissions Displaced by Co-products	0	-12,771
Total	20,200	45,917

* This excludes an emission credit for the use of a renewable source of carbon for production of ethanol.

Table 5-4 Full Cycle Emissions of Greenhouse Gases for Gasoline and a 10% Ethanol Gasoline Blend in 2000

	Gasoline	10% Ethanol Blend
Units	Grams CO_2 equivalent/mile	Grams CO_2 equivalent/mile
Vehicle Operation	370.8	368.6
Fuel Dispensing	0.8	0.8
Fuel Storage and Distribution	4.0	4.2
Fuel Production	44.7	53.4
Feedstock Transport	1.9	2.3
Feedstock and Fertilizer Production	42.0	44.1
Land Use Changes	0.0	0.3
Leaks and Flares	9.8	9.0
Emissions Displaced by Co-products	0.0	-4.5
Carbon in Fuel from CO_2 in Air	0.0	-23.9
Sub-Total	474.0	454.4
Vehicle Assembly and Transport	5.6	5.6
Materials in Vehicles	30.7	30.6
Total	510.3	490.6

% Change		-3.9

The results for the 6 and 8% blends are shown in Table 5-5. The results are slightly less than calculated from simply scaling the ethanol content as the lower level blends do not have quite the same octane benefit within the refinery. Reductions in greenhouse gas emissions are 2.2%, 3.0%, and 3.9% for ethanol blends of 6%, 8% and 10%, respectively. The results are approximately proportional to the ethanol content.

Table 5-5 Impact of Ethanol Content on Greenhouse Gas Emissions in Year 2000

	Gasoline	6% Ethanol	8% Ethanol	10% Ethanol
Total Emissions (grams/ mile CO_2 eq.)	510.3	499.0	494.8	490.6
Change Relative to Gasoline (grams/ mile CO_2 eq.)	0.0	-11.3	-15.5	-19.7
Percent Change Relative to Gasoline		-2.2	-3.0	-3.9
Total Reduction (tonnes CO_2 equivalent)	0.0	275,000	282,000	287,000

The total reduction in greenhouse gas emissions for the year 2000, based on use of 225 million litres of ethanol in a 10 % gasoline blend is 287,000 tonnes of CO_2 equivalent gases. The results for the 6% and 8% blends as shown in Table 5-5 are lower due to a smaller octane credit.

The greenhouse gas emission results for E85 fuel are shown in Table 5-6. This fuel would yield a 37% reduction in greenhouse gas emission for the average new vehicle in 2000.

Table 5-6 Full Cycle Emissions of Greenhouse Gases for Gasoline and E85 for Year 2000

	Gasoline	E85
Units	Grams CO_2 equivalent/mile	Grams CO_2 equivalent/mile
Vehicle Operation	370.8	347.1
Fuel Dispensing	0.8	0.8
Fuel Storage and Distribution	4.0	6.7
Fuel Production	44.7	158.8
Feedstock Transport	1.9	6.5
Feedstock and Fertilizer Production	42.0	68.2
Land Use Changes	0.0	3.5
Leaks and Flares	9.8	1.9
Emissions Displaced by Co-products	0.0	-49.2
Carbon in Fuel from CO_2 in Air	0.0	-259.9
Sub-Total	474.0	284.4
Vehicle Assembly and Transport	5.6	5.6
Materials in Vehicles	30.7	30.8
Total	510.3	320.8
% Change		-37.1

For the year 2010 there will be a number of changes to gasoline and ethanol production and use that will impact on greenhouse gas emissions. These are listed below:

- Vehicle fuel economy will improve from 9.6 L/100 km to 9.0 L100km,
- Gasoline will have a sulphur content of 30 ppm, reducing emissions of carbon monoxide, hydrocarbons and oxides of nitrogen
- Refinery and ethanol plant energy efficiency will improve but the ethanol plant will improve at a higher rate,
- More coal will be used to produce electricity in Ontario

These changes will reduce the greenhouse gas emissions for both gasoline and ethanol blends on a per mile driven basis, but the improvement is greater for ethanol than for gasoline. The emissions results are shown in Table 5-7.

Table 5-7 Full Cycle Emissions of Greenhouse Gases for Gasoline and Ethanol Blended Gasoline for Year 2010

	Gasoline	10% Ethanol Blend
Units	Grams CO_2 equivalent/mile	Grams CO_2 equivalent/mile
Vehicle Operation	341.7	338.9
Fuel Dispensing	0.8	0.8
Fuel Storage and Distribution	3.4	3.6
Fuel Production	50.1	55.0
Feedstock Transport	1.9	2.2
Feedstock and Fertilizer Production	40.5	42.1
Land Use Changes	0.0	0.1
Leaks and Flares	8.5	7.8
Emissions Displaced by Co-products	0.0	-3.6
Carbon in Fuel from CO_2 in Air	0.0	-22.4
Sub-Total	446.7	424.5
Vehicle Assembly and Transport	5.3	5.3
Materials in Vehicles	28.1	28.1
Total	480.1	457.8
% Change		-4.6

The total reduction in greenhouse gas emissions for the year 2010 based on 225 million litres of ethanol in a 10% blend is 342,000 tonnes of CO_2 equivalent gases. The 6 and 8% blends again produce a slightly lower total benefit compared to the 10% level.

The results for E85 for 2010 are shown in Table 5-8. Both fuels have lower emission than in the year 2000 due to improved vehicle fuel economy, more efficient production practices and more efficient plants. As with the cases of the low-level blends, there is a small relative improvement for E85 over gasoline compared to the year 2000. E85 is predicted to yield a 44.5% reduction in greenhouse gas emissions relative to low sulphur gasoline.

Table 5-8 Full Cycle Emissions of Greenhouse Gases for Gasoline and E85 for Year 2010

	Gasoline	E85
Units	Grams CO_2 equivalent/mile	Grams CO_2 equivalent/mile
Vehicle Operation	341.7	317.5
Fuel Dispensing	0.8	0.9
Fuel Storage and Distribution	3.4	6.1
Fuel Production	50.1	122.9
Feedstock Transport	1.9	5.8
Feedstock and Fertilizer Production	40.5	60.4
Land Use Changes	0.0	1.7
Leaks and Flares	8.5	1.7
Emissions Displaced by Co-products	0.0	-39.4
Carbon in Fuel from CO_2 in Air	0.0	-243.6
Sub-Total	446.7	233.2
Vehicle Assembly and Transport	5.3	5.3
Materials in Vehicles	28.1	28.2
Total	480.1	266.7
% Change		-44.5

Table 5-9 shows the emissions of the separate gases that make up the CO_2 equivalent emissions for the years 2000 and 2010. The emissions are categorized into vehicle operation, upstream emissions, and vehicle materials and assembly. The impact of the N_2O emissions from the farming operations is clearly evident with the E85 fuel where N_2O emissions are an order of magnitude higher than the upstream emissions of the gasoline case. There is a trend for CO_2 to constitute a larger portion of the emissions in the year 2010 as vehicles becoming cleaner burning.

Table 5-9 Fuel Cycle Emissions of Individual Greenhouse Gases in 2000 and 2010

	2000			2010		
	Gasoline	10% Ethanol	E85	Gasoline	10% Ethanol	E85
Units	gram/mile	gram/mile	gram/mile	gram/mile	gram/mile	gram/mile
Feedstock	Crude Oil	Crude Oil and Corn	Corn and Crude Oil	Crude Oil	Crude Oil and Corn	Corn and Crude Oil
CO_2						
Vehicle Operation	344	342	320	330	327	305
Upstream	84	68	-91	87	70	-108
Veh Mat'l & Assembly	35	35	35	32	32	32
Total	463	445	265	450	429	230
% Total CO_2 Equiv.	90.8	90.6	82.5	93.7	93.7	86.1
CH_4						
Vehicle Operation	0.167	0.174	0.234	0.157	0.163	0.221
Upstream	0.823	0.824	0.806	0.737	0.728	0.615
Veh Mat'l & Assembly	0.008	0.008	0.008	0.007	0.007	0.007
Total	0.999	1.006	1.048	0.901	0.898	0.843
% Total CO_2 Equiv.	4.1	4.3	6.9	3.9	4.1	6.6
N_20						
Vehicle Operation	0.062	0.062	0.062	0.019	0.019	0.019
Upstream	0.007	0.010	0.039	0.007	0.010	0.038
Veh Mat'l & Assembly	0.001	0.001	0.001	0.001	0.001	0.001
Total	0.070	0.074	0.102	0.027	0.030	0.059
% Total CO_2 Equiv.	4.3	4.7	9.9	1.7	2.0	6.9
Total CO_2 Equiv.	510	491	321	480	458	267

5.3.2 Emissions in 2010 for Production increasing to 1 Billion litres/year

To forecast the emissions for the year 2010 with up to one billion litres of ethanol produced it is necessary to consider what changes if any the extra volume would require over the base case modelled. The impact was considered for three cases, 500 million litres, 750 million litres and one billion litres. In each case it was assumed that 10% ethanol in gasoline would be the fuel.

The analysis in this study developed predictions of the greenhouse gas emissions and an energy balance for each of the selected ethanol production scenario. The feedrate and production rate data for each of these scenarios, and a summary of the emission and energy data is provided in Table 5-10. A discussion of the results for each of the production scenarios is provided in the following sections.

Table 5-10 Summary of Predicted Results for 2010 Ethanol Production Scenarios with a 10% Ethanol Blend

	Ethanol Production Volume (ML/yr)			
	225	500	750	1,000
DDGS Produced (kt/yr)	160	360	535	710
Corn Feedrate (kt/yr)	560	1,250	1,875	2,500
Predicted Fuel Cycle Emissions (g/mile):				
CO_2	429	429	429	430
CH_4	0.90	0.90	0.90	0.90
N_2O	0.03	0.03	0.03	0.03
Total CO_2 Equivalent	458	458	458	459
Predicted CO_2 Equivalent Emission Reduction Relative to Gasoline:				
(g/mile)	22.3	22.3	22.3	21.3
(ktonnes)	346	770	1,155	1,470
Energy Balance (PJ)				
Energy Output in Ethanol (A)	5.31	11.79	17.69	23.58
Effective Energy in Vehicle (B)	6.26	13.91	20.87	27.82
Total Energy Inputs	3.65	8.11	12.17	16.38
Co-Product Credits	0.73	1.62	2.43	3.24
Net Energy Inputs (C)	2.92	6.49	9.74	13.14
Net Energy Output in Fuel (A-C)	2.39	5.30	7.95	10.44
Net Effective Energy Output in Vehicle (B-C)	3.34	7.42	12.92	14.68

5.3.2.1 Ethanol Production of 500 Million Litres per Year

Ethanol production of 500 million litres per year will require 1.25 million tonnes of corn annually. This is about 25% of the current crop, but with the increase in crop yield expected by 2010, it will instead amount to about 20% of the total production, assuming the same land base. The corn required for ethanol production will be is less than the increase in corn demand because of the corn displaced from use of co-produced DDGS. Therefore, no changes are necessary to the corn production model inputs.

It is assumed that the additional plant capacity will be located in a region of concentrated corn production and that transportation distances from the farm to the ethanol plant will not change. Transportation distances for DDGS are already large in the model, which reflects the start up strategy of the existing ethanol plant (move the product over a large area so that the supply and demand balance is not impacted and prices are not lowered). Over time it is expected that more of the DDGS product can be sold to markets closer to the plant. The transport distances for the 500 million litre case are assumed to not change over that modelled.

No improvements in the technology for production of ethanol have been assumed to take place by 2010. We have assumed that the ethanol plant will take full advantage of existing technology to lower the energy required to produce ethanol. The improvements in operating practices will put the energy efficiency in the top quartile of current ethanol plants in the US. It is believed that this is a conservative assumption.

No changes are required for the refinery inputs. The additional ethanol would likely be used in a second plant at the 10% level and not in all plants at the 5% level. The results from the 225 million litres per year case can be reasonably scaled to 500 million litres per year. The total greenhouse gas emission reduction potential is 770,000 tonnes of CO_2 equivalent emissions.

5.3.2.2 Ethanol Production of 750 Million Litres per Year

Ethanol production of 750 million litres per year will require 1.87 million tonnes of corn or about 30% of the expected 2010 crop. This can theoretically be met with displacing some corn from the animal feed market with DDGS and the increase in production from the higher yield expected. The other assumptions made for the 500 million litres per year case are also valid and the greenhouse gas emission reduction potential is 1.155 million tonnes per year of CO_2 equivalents.

5.3.2.3 Ethanol Production of One Billion Litres per Year

Ethanol production of one billion litres per year will require 2.5 million tonnes of corn. Due to the limitations of crop rotations in Ontario it is unlikely that significant amounts of Ontario soybean acreage will be switched to corn. Some of this corn will therefore be imported from the United States. The US corn may come from land that switched from soybeans to corn due to the reduced demand for soybean meal caused by the increased production of DDGS or it may come from the increased crop size due to increasing yields. The US corn does have an impact on greenhouse gas emissions from corn production and from increased transportation distances compared to Ontario corn.

Greenhouse gas emissions from US corn production are expected to be slightly higher than those projected for Ontario corn. This arises from the higher energy required for the nitrogen fertilizer because of less manure being used, small increases in other fertilizer application rates offset partially by less energy used in the drying of the corn. The feedstock transport emissions will also increase due to longer trucking distances. The net impact of these changes will be to reduce the benefit of ethanol blends by between 2 and 3 grams of CO2 equivalent per mile travelled. This will lower the percent change from 4.6% to 4.0% on the ethanol volume between 750 million and one billion litres of ethanol. The total emission reduction potential amounts to 1.47 million tonnes of CO2 equivalents.

5.3.3 Comparison of Predicted GHG Emissions to Results from Other Studies

There have been a number of studies done over the past ten years. Most of these have examined the situation in the United States, the one Canadian study (Cemcorp, 1992) looked at the energy balance and the carbon dioxide emissions only. Cemcorp reported a 4.2% reduction in CO_2 for a 10% ethanol blend, and did not consider emissions of methane and nitrous oxide. The Cemcorp study had a very detailed look at the energy required for corn farming in Ontario, which is still some of the best data available. Energy requirements for the plant were lower than that used for the current study. The co-product credits were based on the metabolizable energy content of the DDGS compared to corn when fed to cattle.

Wang (1997) summarized the results of eight US studies of corn ethanol for mostly high level blends (E85 to E100). The results reported by Wang are shown in Table 5-11.

Table 5-11 Summary of Major Corn-Ethanol Studies (From Wang 1997)

Author	Fuel	Range of Changes in Full Cycle GHG Emissions	Remarks
US EPA, 1989	E100	-22% to –21%	CO_2 only, co-products are based on displaced products
	E85	-6% to –5%	
Ho, 1990	E100	-15% to -36%	The range reflects assumptions about ethanol production technology
Marland, 1990	E100	-40% to -20%	Co-product credits are based on both market values and displaced products
Delucchi, 1991	E100	-65% to +80%	Coal as process fuel
		-70% to 0%	Natural gas as process fuel
Amhed, 1994	Ethanol in gasoline	-35% to 0%	Coal as process fuel
		-40% to –10%	Natural gas as process fuel
		-60% to –40%	Corn stover as process fuel
Delucchi,1996	E95	+20.6%	
Wang,1996	E100	-31.7%	Co-products based on energy content
	E85	-25.4%	Coal as process fuel
Wang,1997	E85	-18.2%	Coal as process fuel and co-products based on market values
	E85	-30.5%	Natural gas as process fuel and co-products based on market values

There is a wide range of values reported, as is apparent from the table. Most of the results also looked at high level blends and not low-level blends. Wang has published two subsequent reports (1997 and 1999) and Delucchi has a new version of his model (1998) that calculates the corn-ethanol cycle. These three studies consider both 10% blends and E85. These three studies also take advantage of more recent data for almost all aspects of the fuel cycle.

Wang (1997) studied the corn ethanol cycle for four Midwestern states using his GREET model. The process energy is supplied 50% by coal and 50% by natural gas. The results for dry milling plants from that study are shown in Table 5-12 and 5-13. Wang assumes different types of vehicles for E10 and E85, so the base fuel economy and the related gasoline emission rates are different.

The E85 and E10 percentage changes are lower than what we have calculated (-37.1% for E85 and –3.9% for E10). Reviewing the input data, the significant differences are the use of coal and natural gas for the plant process heat, however that is offset by a lower use of process heat in Wang's model. Wang does not adjust the energy specific fuel economy for the E10 case although he does reference that it should be better for the E10 based on reported in-use experience. The E85 case has a similar relative energy efficiency to that which we modelled. Wang's N_2O values for the ethanol case are much higher than is used in this study. The nitrogen application rates are similar, as is the rate of conversion of nitrogen to N_2O, but Wang does not calculate an offset for carbon growth caused by the run-off of nitrogen. Delucchi notes that this can be about 50% of the N_2O produced. Correcting for this difference would make the results much closer.

Table 5-12 Fuel Cycle Emissions for E10 from Corn Reported by Wang (1997)

Units	Gasoline grams/mile	E10	
		grams/mile	% Change
Total Greenhouse Gases (CO_2 Equiv.)	382.7	373.6	-2.4
CO_2	370.9	358.3	-3.4
CH_4	8.9	8.5	-4.5
N_2O	2.9	6.8	+134.5

Table 5-13 Fuel Cycle Emissions for E85 from Corn Reported by Wang (1997)

Units	Gasoline grams/mile	E85	
		grams/mile	% change
Greenhouse Gases	469.1	324.7	-30.8
CO_2	455.4	264.3	-42.0
CH_4	10.5	4.2	-60.0
N_2O	3.2	56.2	+1656

Wang (1999) updated his work from 1997 with respect to two issues, the source of land to support a doubling of US corn ethanol production, and the displacement method for co-product credit calculations. In Section 3.2.4 we discuss the land use issue and Wang's approach. The co-product displacements that Wang uses are fundamentally sound. The 1999 report has very little input data specified and few assumptions detailed. The GHG reductions are lower than reported in 1997, but it is difficult to determine the reasons for the changes. The results from this more recent analysis are shown and compared to the results from the 1997 study in Table 5-14.

Table 5-14 Comparison of the Greenhouse Gas Emission Reduction Predictions for E10 and E85 Developed by Wang (1997 & 1999)

	E10	E85
Wang (1997)	-2.4%	-30.8%
Wang (1999) current case	-1.3%	-18.8%
Wang (1999) future case	-1.8%	-25.5%
This report for year 2000	-3.9%	-37.1%
This report for year 2010	-4.6%	-44.5%

The Delucchi model as developed for the US (Delucchi, 1998) can be used to calculate emissions for E10 and E85 from corn. The model results for the year 2000 with all of Delucchi's assumptions are shown in Table 5-15.

Table 5-15 Comparison of GHG Emission Reduction Estimates Developed by Delucchi

	E10	E85
Delucchi 1998	-0.9%	-19.2%
This report for year 2000	-3.9%	-37.1%

The emissions for the production of ethanol are about 50% higher in Delucchi's case than in our model, primarily for the following three reasons:

- A portion of the ethanol plant process energy comes from coal; this accounts for 46% of the difference between the two cases. Delucchi actually uses less energy than our case;
- Delucchi assumes that 5% of the land is deforested and 60% comes from pasture, this accounts for 40% of the difference; and
- Energy required for fertilizer production is higher due to the use of chemical fertilizer and slightly higher application rates than in Ontario, resulting in 10% of the difference.

There are other small differences in assumptions, such as trucking distances and the emissions from electricity production, reflecting the site-specific nature of the analyses.

5.4 NON-GREENHOUSE GAS EMISSIONS FOR ETHANOL BLENDS AND GASOLINE

The model used is also capable of calculating the life cycle emissions for non-greenhouse gas emissions. This compares emissions from all aspects of production and use of the fuel. The results for gasoline, 10% ethanol blends and E85 are presented in Table 5-16 for the year 2000. The information is also segregated by vehicle operation, upstream and vehicle material and assembly.

Table 5-16 Fuel Cycle Non-Greenhouse Gas Emissions for Gasoline, E10 and E85 in 2000

	Gasoline	E10	E85
Units	gram/mile	gram/mile	gram/mile
CO			
Vehicle Operation	10.888	9.545	7.389
Upstream	0.589	0.571	0.374
Vehicle Mat & Assembly	0.008	0.008	0.008
Total	11.485	10.124	7.772
NO_x			
Vehicle Operation	1.107	1.098	1.018
Upstream	0.721	0.737	0.862
Vehicle Mat & Assembly	0.060	0.060	0.060
Total	1.887	1.895	1.940
VOC-ozone weighted			
Vehicle Operation	1.202	1.038	0.780
Upstream	0.406	0.459	0.961
Vehicle Mat & Assembly	0.002	0.002	0.002
Total	1.610	1.498	1.743
SO_x			
Vehicle Operation	0.099	0.042	0.042
Upstream	0.199	0.193	0.095
Vehicle Mat & Assembly	0.096	0.096	0.096
Total	0.394	0.331	0.234
Particulate Matter			
Vehicle Operation	0.049	0.027	0.025
Upstream	0.000	0.000	0.000
Vehicle Mat & Assembly	0.011	0.011	0.011
Total	0.060	0.038	0.036

5.5 SENSITIVITY OF GHG EMISSIONS AND ENERGY BALANCES TO CHANGES IN INPUT DATA

The calculation of total greenhouse gas emissions is the sum of a large number of small calculations. The potential for a large change in emissions based on one assumption is therefore reduced. There are some assumptions that can make some difference and the sensitivity to these is explored. The variables considered are:

- No manure use for fertilizer
- Changes in rate of conversion of nitrogen to N_2O
- No octane credit in the refinery
- Energy efficient ethanol plant
- Use of corn stover as a fuel instead of natural gas.

The sensitivity of changes in these variables to the energy balance and the full cycle greenhouse gas emissions for the year 2000 are shown in Table 5-17.

Table 5-17 Sensitivity Analyses for differing Inputs

	% Change in Energy Input	GHG Emissions Reduction for E10
Base case		-3.9%
No manure for nitrogen fertilizer	+6.2	-3.8%
Reduce rate of N to N_2O to 0.65%	0	-4.1%
Increase rate of N to N_2O to 1.6%	0	-3.8%
Remove refinery Octane Credit	+1.5	-3.8%
Reduce energy use in the ethanol plant by 27%	-21.7	-4.6%
Use corn stover for plant fuel instead of natural gas	0	-6.3%

The use of corn stover as the fuel for plant heat requirements produces the largest change in GHG emissions, but no change in energy input. There is a reduction in petroleum energy use, but no overall change in energy use. The next largest change is with the assumption of state-of-the-art energy use in the ethanol plant. This is followed by the impact of the rate of conversion of nitrogen to N_2O.

5.6 THE POTENTIAL FOR CORN ETHANOL TO CONTRIBUTE TO MEETING CANADA'S COMMITMENT UNDER THE KYOTO PROTOCOL

In December 1997, the parties to the 1992 United Nations Framework Convention on Climate Change (FCCC) adopted a protocol to the Convention (the Kyoto Protocol) to limit emissions of greenhouse gases. The Protocol will come into force when fifty-five countries covering a minimum of fifty-five percent of the FCCC Annex 1 countries emissions, have ratified the protocol. Canada is an Annex 1 country and has accepted a GHG reduction target of six percent below its 1990 level of 564 Mt CO_2 equivalent by the end of the first reporting period, 2008-2012.

Analysis conducted by Environment Canada indicates that Canada's net GHG emissions need to be reduced by 21-26 percent, or approximately 140 to 185 million tonnes, below the level projected to occur in 2010 under a business-as-usual scenario to achieve the six percent reduction target. This is a very difficult challenge for Canada given its growing population, cold climate, long transportation distances, and the fact that our exported raw materials contain significant embedded fossil fuel emissions.

Emissions of greenhouse gases from Canadian road transportation sources in 1995 totalled approximately 123 Mt (Jaques et al, 1997). This amounts to about 19.9% of the total CO_2 equivalent greenhouse gas emissions from energy and non-energy sources in 1995 (23.8% if considering only energy sources) and about 74.3% of the total greenhouse gas emissions from the Transportation Sector. The greenhouse emissions from the road transportation sector arise 51.1% from automobiles, 26.0% from heavy-duty trucks and buses and 22.8% from light-duty trucks, with the remainder being from motorcycles.

Ethanol produced from corn in Ontario and blended with gasoline will reduced emissions of greenhouse gases. If ethanol production can be expanded to one billion litres per year by 2010 then emissions of GHG can be reduced by 1.47 million tonnes annually. This represents 0.8 to 1.0% of the total reduction required to meet Canada's commitment to the Kyoto Protocol. It also represents 5.8 to 7.5% of agriculture's share of the required reduction or 3 to 4% of the transportation sector's share.

Ontario represents about one third of Canada's gasoline demand and about 70% of the corn supply. Using ethanol in more of Canada's gasoline would require use of additional agricultural crops, such as wheat, as a feedstock. The use of crops in addition to corn could increase the total amount of ethanol produced in Canada, but a full cycle analyses would have to be done to determine their different fuel cycle greenhouse gas emissions, as each crop requires different fertilizer inputs and energy use for tillage, planting, harvesting and drying.

6. Data Gaps and Uncertainties

Reasonably accurate and current information was available to the study team for the most important parameters used to predict greenhouse gas emissions for the study. The data used in the model for this study yields a tool that predicts fuel cycle greenhouse gases for Southern Ontario and other similar regions of Canada more accurately than has been previously possible.

Data on farm energy use in Canada is not available to the same degree as it is in the United States. Nevertheless the data that is available correlates well with the more comprehensive US data and is believed to be accurate and representative of actual on farm energy use.

The ethanol plant data is based on actual experience with corn ethanol production in Ontario. Energy use, transportation distances for raw materials and products reflect current conditions and are thought to be very accurate.

The refining energy is representative of a typical Ontario refinery. The data does not represent any of the five refineries specifically, but is a composite of the industry. The data is consistent with energy use in refineries reported by the CPPI.

The largest area of uncertainty is with the conversion of nitrogen fertilizer used in the farming practice to N_2O. Agriculture and Agri-Food Canada (1999) has reported a range of conversion rates that are lower than that assumed for this study. Other researchers such as Wang have used rates that are slightly higher than used in this study and do not take into account secondary effects.

There is uncertainty over changes in soil organic carbon that may arise from different farming practices such as zero or conservation tillage. It has been assumed that the land being cultivated has been in cultivation for many years and has a relatively low rate of carbon loss. There have been reports of soil carbon increases of 0.1 kg-C/m^2 (Ontario Corn Producer 1994) with corn grown using zero tillage compared to traditional tillage methods. There was insufficient data available to support an increase in SOC. The uncertainty on SOC is less than that on N_2O.

7. Conclusions

Ethanol produced from corn in Ontario and incorporated into a refinery blending system is capable of reducing greenhouse gas emissions by 3.9% compared to conventional gasoline using existing farming, refining, and ethanol production practices and conservative assumptions regarding co-product credits. By the year 2010 this reduction is projected to increase to 4.6% based on the following assumptions:

- Low sulphur gasoline will be produced which requires more energy to produce,
- Ethanol plant energy use will decrease based on the best use of existing technology,
- There will be a continuing improvement in energy efficiency in gasoline refining and farming practices,
- Corn yields will continue to improve as will the inputs required to grow corn at the same rate as historical changes.

The current ethanol use of about 150 million litres per year reduces GHG emissions by 230,000 tonnes per year.

If the industry is expanded to produce one billion litres of ethanol per year by 2010 the total GHG reductions will be 1.47 million tonnes of CO_2 equivalents annually.

These values are dependent on the use of ethanol in such a manner that its high-octane properties can be fully utilized. The recent changes in the allowable gasoline sulphur content may put an octane strain on most Ontario refineries. The extent of the octane shortage will be a function of the technology that refiners use to remove the sulphur. The use of 10% ethanol should be enough to eliminate that octane shortage caused by the de-sulphurization of the gasoline in most refineries. The use of ethanol would reduce the capital that refiners would otherwise have to invest in new octane generating capacity. There will be a limited window of opportunity to take advantage of this situation. Refiners will soon be committing to significant capital expenditures to remove sulphur.

Ethanol production in Ontario has a positive energy balance. For the year 2000, the ethanol contains 50% more energy than was required to produce it. If ethanol's octane value and higher combustion efficiency are considered the effective energy represented by the ethanol is 83% higher than the energy required to make it. The ratio of actual and effective energy output increases to 82% and 123% more than the input energy, respectively, by 2010.

The energy balance and greenhouse gas emission situation is expected to improve over the next decade primarily due to anticipated improvements in energy use during the ethanol production process as the existing plant reduces their energy use to be more in line with energy use at similar US plants.

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Appendix A Supporting Data for Fuel Cycle Analysis

PRODUCTION OF BIOMASS									
A. Fertilizer and pesticides (lbs/bu-to-plant, lbs/ton-wood-to-plant)									
	N	P_2O_5	K_2O	Lime	Sulfur	Pesticides	Seeds		
	lbs	Lbs	lbs	lbs	lbs	lbs	lbs		BTUs
Corn (per bushel)	Formulas (refers to sheet W)							Base years:	
Value in base year (1994)	1.075	0.353	0.47	0	0	0.01	0.03	1994	23,102
Percent change/year	-0.5	-1	-1	-2	-2	-0.3	0		n.a.
Value in target year (2000)	1.043	0.332	0.443	0	0	0.009	0.03		22,358
Soybeans (per bushel)									
Value in base year (1994)	0.102	0.316	0.612	0	0	0.034	1.8	1994	12,725
Percent change/year	-0.5	-1	-1	-2	-2	-0.3	0		n.a.
Value in target year (2000)	0.099	0.298	0.576	0	0	0.033	1.8		12,441

B. Fuel and power use								
	Diesel	Residual fuel	Natural gas	Coal	Electricity	Gasoline	LPG	Biofuel itself
	gallons	gallons	1000 CF	lbs	kWh	gallons	gallons	gallons
Corn (per bushel)								
Value in base year (1994)	0.043	0	0.008	0	0	0	0.094	0
Percent change/year	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Value in target year (2000)	0.042	0	0.008	0	0	0	0.092	0
Soybeans (per bushel)								
Value in base year (1994)	0.177	0	0.002	0	0.139	0.105	0.012	0
Percent change/year	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Value in target year (2000)	0.173	0	0.002	0	0.136	0.103	0.012	0

EMISSIONS RELATED TO FERTILIZER USE and CULTIVATION

Corn	Soybean	
0.013	0.011	N-N2O/N-fertilizer applied, direct or "on-site" emissions, in base year 1994
0.25	0.25	N lost offsite through drainage or runoff, fraction of N applied, in base year 1994
0.4	0.4	of N lost offsite, fraction that fertilizes terrestrial ecosystems (rest fertilizes aquatic, including marine)
0.013	0.013	N-N_2O/N-fertilizer-offsite
-0.5	-0.5	Annual percentage change in on-site emission rate, and offsite N leaching rate
0.04	0.04	N-NOx/N-fertilizer applied
0	0	g-CO_2 (soil)/g-N-fertilizer
0.1	0.1	g-CH_4 (soil)/kg-N-fertilizer
25	25	g-CH_4 (soil)/ha/year, independent of fertilizer rate
116	36	Harvest yield in base year of 1996 (SHOULD BE CONSISTENT WITH BASELINE FERTILIZER LOSS RATE)
1.5	1	Change in harvest yield (%/year) (SHOULD BE CONSISTENT WITH CHANGE IN FERTILIZER LOSS RATE)
n.e.	n.e.	Harvest losses (fraction of standing yield)
0.02	0.02	Post-harvest losses (fraction of harvest yield)
n.a.	n.a.	Years of growth before first harvest
0.15	n.a.	Moisture content as shipped (moisture weight/dry weight) (value for corn is for corn residue)
Assume 1.0	1	Acreage fraction fertilized
		CALCULATED RESULTS
123.1	37.5	Standing yield per acre in target year(bushels for corn, soybeans; tons for wood, grass)
123.1	37.5	Harvest yield per acre in target year (bu for corn, soy; dry tons for wood, grass)
120.7	36.7	Into-plant yield per acre in target year, net of harvest and hauling losses (bushels for corn, soybeans; net tons for wood, grass)

-145,973	-9,688	g-CO_2 (soil+biomass)/acre, due to cultivation
0.015	0.013	Total N-N2O/N-fertilizer applied, in target year
-4.53	-4.53	g-CO_2/g-N fertilizer applied, due to fertilization of terrestrial and aquatic ecosystems by run-off nitrogen fertilizer (negative emission means CO2 uptake)
27.5	5.9	g-CO_2-equivalent emissions from soil methane, per bushel (corn, soybeans)

Years over which soil loss occurs	25	NOTE: liming may decrease N2O emissions;
Years over which biomass loss occurs	15	be consistent
interest rate, for carbon losses	0.02	

Fuel Characteristics Used in the Fuel Cycle Model

FUEL	Higher heating values	Units	Value	Units	Density Value	Units	Carbon fraction	Sulfur fraction
Crude oil input to refineries (Year 2010)	0.1381	mmBTU/gal	5.800	mmBTU/bbl	3338	g/gal	0.850	0.01337
Residual fuel oil	0.1497	mmBTU/gal	6.287	mmBTU/bbl	3575	g/gal	0.858	0.00992
Diesel fuel	0.1387	mmBTU/gal	5.825	mmBTU/bbl	3192	g/gal	0.858	see above
F-T diesel from NG	0.1310	mmBTU/gal	22,260	g/mmBTU	2916	g/gal	0.848	0.00001
Canola diesel (was Soydiesel)	0.1325	mmBTU/gal	25,251	g/mmBTU	3346	g/gal	0.770	0.00008
DME (density, LHV from SAE paper 971607, HHV calced)	0.0751	mmBTU/gal	33,307	g/mmBTU	2501	g/gal	0.522	0.00001
Petrol diesel, biodiesel, and F-T diesel mix	0.1375	mmBTU/gal	23,446	g/mmBTU	3223	g/gal	0.840	0.00025
Petroleum coke	0.1434	mmBTU/gal	6.024	mmBTU/bbl	4321	g/gal	0.900	0.00800
Conventional gasoline	0.1251	mmBTU/gal	5.253	mmBTU/bbl	2791	g/gal	0.866	0.00032
Reformulated gasoline	0.1251	mmBTU/gal	5.253	mmBTU/bbl	2791	g/gal	0.866	0.00003
Reformulated gasoline: petroleum component only					2791	g/gal		
Gasoline used in tractors and engines	0.1251	mmBTU/gal	5.253	mmBTU/bbl	2791	g/gal	0.866	0.00003
Methanol	0.0645	mmBTU/gal	46,446	g/mmBTU	2996	g/gal	0.375	0.00001
Methanol/gasoline mix	0.0736	mmBTU/gal	40,294	g/mmBTU	2965	g/gal	0.444	0.00001
Ethanol	0.0846	mmBTU/gal	35,319	g/mmBTU	2988	g/gal	0.522	0.00001
Ethanol/gasoline mix	0.0907	mmBTU/gal	32,629	g/mmBTU	2958	g/gal	0.570	0.00001
Generic industrial coal	21.032	mmBTU/ton	10,516	BTU/lb			0.598	0.00904
Utility coal	19.703	mmBTU/ton	9,851	BTU/lb			0.562	0.00904
Coal to Methanol	19.703	mmBTU/ton	9,851	BTU/lb			0.562	0.00904
Hydrogen	7470	g/mmBTU	338	BTU/SCF				
Refinery -made LPG	0.0920	mmBTU/gal	3.863	mmBTU/bbl	2053	g/gal		0.00001
LPG assumed in this analysis	0.0914	mmBTU/gal	3.838	mmBTU/bbl	1917	g/gal		0.00001
Electricity			3412	BTU/kwh				
Steam			1.200	mBTU/lb				
Petroleum products produced in U. S. (generic)			5.395	mmBTU/bbl	0.1497	ton/bbl		
Other refinery oil			5.825	mmBTU/bbl				
Lube oil	0.1444	mmBTU/gal	6.065	mmBTU/bbl	3401	g/gal	0.858	0.00992
Wood	16.7	mmBTU/dt	8350	BTU/dry-lb			0.520	0.00090
Grass	15.0	mmBTU/dt	7500	BTU/dry-lb			0.484	0.00090
Butanes	0.103	mmBTU/gal						
Isobutylene	0.090	mmBTU/gal						

LIGHT-DUTY VEHICLE EMISSIONS (gasoline)					
		Input conventional gasoline			E10 Emissions RELATIVE to conventional gasoline
	Year 2000	Deterioration rate	Zero-mile, MY 1993		
Pollutant	G/mi	g/mi/10000-mi	% change per MY year	g/mi in base year	
Fuel evaporation or leakage	0.37	0.02	-1.7	0.26	1
NMOC exhaust	0.92	0.0509	-5.5	0.84	0.91
CH4 exhaust	0.17	0.015	-3.5	0.08	1
CO exhaust	10.89	0.6829	-6	9.42	0.9
N2O exhuast	0.062	0	-3.5	0.08	1
NOx as NO2 exhaust	1.11	0.0281	-5	1.3	1
PM exhaust	0.05	0.005	-5	0.02	1
Consumption of lube oil*	1.64	n.a.	n.a.	1.64	1

Appendix B Summary of Changes to Model

Changes to Model after June 21,1999

Note: June 21 was the last version of Model for NRCan study. This data is for the year 2000.

Sheet C	H29 and H30 set to 1.06 from 0.95 to effect a 1% improvement in E10 Efficiency Change for E85 and 2010 E6 changed to 21.95 year 2000 fuel economy E7 changed to 28.54 year 2000 fuel economy
Sheet D	
	Q183 set to 0 Q184 set to 1.0 D183-D188 change to Ontario only
Sheet E	
	D49 to 49.0 to match D50 A98 Soydiesel title
Sheet F	
	F94 Soydiesel title C8 change from 0.85 to 1.0 (same evap emissions for E10)
Sheet G	
	B40 change gasoline from 0.123 to 0.1127 for 1996 baseline C40 to 0.1078 for a 10% blend (octane credit) C40 to 0.1088 for a 8% blend (octane credit) C40 to 0.1098 for a 6% blend (octane credit) Change C40 to 0.1112 from 0.1127 to account for octane credit of ethanol P9 set multiplier to 1 (same as CG) P10 set multiplier to 1 (same as CG) P14 set multiplier to 1 (same as CG)
Sheet H	F34 from 0.7 to .91 F36 from 0.8 to 0.9 F37 from 0.4 to 1.0 F38 from 0.85 to 1.0
Sheet K	
	K22, K102 and various other places changed canola to soy
Sheet S	
	B27 adjust crude oil factor for the Ontario blend vs national av (87%) National should be 5.05 and Ontario is 4.4 and calibrate to Capp data
Sheet U	
	H35 Soybeans J80 Soybeans B57 pipeline distance is 2400 miles Alberta to Ontario B108 is set to 75 miles B101 is set to 250 miles B100 and B106 are set to 1 other modes are set to zero

Sheet V

A12 Soybeans
C13 original value 0.31
D13 original Value 0.6
E64 set to 45 miles
H82 set to zero
H106 set to 1.0
H108 set to 140 miles
B30 set to 0.042
C,e,f,g 30 set to 0
H30 set to 0.092
G9 set to 0.0094
D30 set to .00819

Sheet W

C146 original value 0.1
A146 changed to soy
C145 changed to 1.075 lb/bu
C9 changed to 0.346 lb/bu
D9 changed to 0.461 lb/bu
E9 changed to 0
F9 changed to 0
G9 changed to 0.019
B42 multiple by 0.65 to account for energy saved by using manure
B185 set to 0
C185 set to 0.0
D185 set to 0.2
E185 set to 0.8
C138 set to 1.5% to equal past rate
D171 from 0.1 to 0.0026

Sheet X

J5 changed to soybean
X23 back to original value
G29 changed to 0.08
G31 changed to 0.046
G33 changed to 0.078
G36 changed to 0
C50 changed to 0.279
C51 changed to 50,550
G11 changed to .000115
G6 base year from 1996 to 1999
G15 improvement rate from 0.3 to 2.3%

Sheet Y

A29 remove canola
A31-A34 back to original values
A17 set to 6.7
B13 change formula to (51-12.9) instead of 41-10 to better fit the data
B32 changed to 1.0 from 0.75
A14 set to 2.92 to simulate the Wang displacement factors of DDGS

Sheet Z

To remove imports change AB 23 and 24 to 0.0005 and AB 24 to 0.999

Sheet AA

B10 set to 21.5 to calibrate methane to CAPP for the split of crude going to Ontario refinery

For E85 Blend with conventional gasoline on sheet E
Set H29 and H30 on sheet C to 1.005 from 1.06 to give 5% better fuel economy

Changes to Model after NrCan Project to Model Ontario Corn

Note: Data for the Year 2010

Sheet C H29 and H30 set to 1.06 from 0.95 to effect a 1% improvement in E10 efficiency
H31 and H32 set to 1.45 from 2.3 to effect a 1% improvement in E10 efficiency
E6 and 7 set to 2010 fuel economy
H29 to H32 must be reset for E85 to 1.12

Sheet D

Q183 set to 0
Q184 set to 1.0
O 183 to O188 change to Ontario only for petroleum refining

Sheet E

D49 to 49.0 to match D50
A98 Soydiesel title

Sheet F

F94 Soydiesel title
C8 change from 0.85 to 1.0 (same evap emissions for E10)

Sheet G

B40 change gasoline from 0.123 to 0.1357 for 1996 baseline and lo Sulphur
C40 to 0.1308 for a 10% blend (octane credit)
C40 to 0.1318 for a 8% blend (octane credit)
C40 to 0.1328 for a 6% blend (octane credit)
P9 set multiplier to 1 (same as CG)
P10 set multiplier to 1 (same as CG)
P14 set multiplier to 1 (same as CG)

Sheet H F34 from 0.7 to .91
F36 from 0.8 to 0.9
F37 from 0.4 to 1.0
F38 from 0.85 to 1.0
To account for emission reductions for low sulphur gasoline the following annual improvement factors
d34 from 5.5 to 9.9
D36 from 6.0 to 9.0
D37 from 3.5 to 8.0
D38 from 5.0 to 6.5

Sheet K

K22, K102 and various other places changed canola to soy

Sheet S

B27 adjust crude oil factor for the Ontario blend vs national av (87%)
National should be 5.05 and Ontario is 4.4 and calibrate to Capp data

Sheet U

H35 Soybeans
J80 Soybeans
B57 pipeline distance is 2400 miles Alberta to Ontario
B108 is set to 75 miles
B101 is set to 250 miles
B100 and B106 are set to 1 other modes are set to zero

Sheet V

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B32 changed to 1.0 from 0.75
A14 set to 2.92 to simulate the Wang displacement factors of DDGS

Sheet Z To remove imports change AB 23 and 24 to 0.0005 and AB 24 to 0.999

Sheet AA

B10 set to 21.5 to calibrate methane to CAPP for the split of crude going to Ontario refinery

For E85 Use conventional gas for blending
H31 and H32 set to 1.12 from 1.45 to get 5% improvement in energy efficiency

Appendix C Glossary of Refining Terms

ALKYLATE. High-octane gasoline blending component produced in the refinery by a chemical reaction called alkylation. Basically, isobutane is chemically combined with olefins (e.g. propylene and butylene) in the presence of an acid catalyst to make the product. Normally, there are two types of alkylates used in gasoline blending. C3 and C4 alkylates with the C4 being higher octane and a better quality blending stock.

AROMATICS. Hydrocarbons characterized by the unsaturated benzene ring structure of carbon atoms. Common known ones are benzene, toluene, and xylene (BTX)

ATMOSPHERIC CRUDE OIL DISTILLATION. Commonly referred to as a Crude Unit. It is the refining process that separates crude oil into the various fractions by the use heat at atmospheric pressure in a large distillation column. The fractions usually consist of C4 and lighter, naphtha, light distillate, heavy distillate, virgin gasoil (VGO), and atmospheric tower bottoms. A specific temperature boiling range designates each of the fractions.

BARREL PER CALENDER DAY (BPCD). The maximum number of barrels that can be processed on average in 24 hours, 365 days of the year. This takes into account shutdowns, slowdowns, environmental constraints, scheduled downtime for routine maintenance and inspection, as well as unscheduled downtime such as mechanical problems and repairs.

BARREL PER STREAM DAY. The maximum number of barrels per day that can be processed at full equipment capacities under ideal conditions in any 24 hour period.

BENZENE. A high-octane, aromatic hydrocarbon that is produced mostly by the reforming of naphtha in a catalytic hydrogen reformer. It is considered highly carcinogenic and the amount allowed in motor fuel is limited.

BUTANE. A light hydrocarbon possessing high-octane properties but has very high vapour pressure and therefore has only limited use in the total blend. There are three different butanes; Normal butane, preferred in gasoline blending because it has a lower vapour pressure than isobutane. Isobutane, important feedstock for an alkylation unit. Butylene an olefinic hydrocarbon and an important feedstock for alkylation. All three butanes are produced during the crude oil refining process in varying amounts depending on the process.

CATALYTIC CRACKING. Common term referred to the Fluid Catalytic Cracking Unit (FCCU). The refining process of breaking down larger, heavier and more complex molecules into simpler, lighter and more valuable molecules. The process employs a solid fine catalyst that is fluidized and continuously regenerated.

CATALYTIC HYDROCRACKING. A refining process that uses hydrogen and a catalyst with relatively low temperatures and high pressures to convert middle to high boiling low value materials to higher value reformer feedstock and / or high grade fuel oils.

CATALYTIC REFORMING. A refining process that converts paraffins and naphthenes into high octane blending components by using precious metal catalyst in a hydrogen atmosphere at high temperatures and various pressures. The two common types of reformers are; Semi–Regen, this requires periodic shutdowns to regenerate the catalyst to maintain sufficient activity. Continuous, with a continuous regenerating reformer, the catalyst is maintained at peak activity level at all times.

FLEXICOKING. A thermal process cracking process which converts heavy hydrocarbons such as crude oil, tar sands bitumen, and heavy distillation residues into lighter hydrocarbons.

FLUID COKING. A thermal cracking process utilizing the fluidized-solids technique to remove coke for continuous conversion of heavy, low-grade materials into lighter products.

ISOMERIZATION. A refining process which changes the arrangement of atoms in the molecule without adding or removing anything from the original material. It is used to convert normal butane to isobutane and pentane (C5) and hexane (C6) into high-octane isopentane and isohexane.

MIDDLE DISTILLATES. A general classification that includes kerosene, kerosene- type jet fuels, diesels and distillate fuel oils.

MAXIMUM GASOLINE OPERATION. The refining can operate to maximize gasoline production or to minimize gasoline production. This flexibility allows changes to meet seasonal demand pattern shifts. For a typical refinery the difference between maximum and minimum gasoline can be up to 10% of the refinery crude charge depending on the type and gravity of the crude processed.

MAXIMUM DISTILLATE OPERATION. Normally, a maximum distillate operation goes along with a minimum gasoline operation. The flexibility noted under maximum gasoline heading is between gasoline and distillate. It is generally accomplished by altering the cut point of the two off the crude tower.

NAPHTHA. A generic term applied to a petroleum fraction with an appropriate boiling range between 121 degrees F. and 400 degrees F.

VACUUM DISTILLATION UNIT. A process of distillation at less than atmospheric pressure, which lowers the boiling point of the material being, distilled. Normal feed to the unit is atmospheric tower bottoms. Main products from the unit are light vacuum gasoil, catalytic cracker feed, and vacuum tower bottoms.

VISCBREAKING. A thermal cracking process in which heavy atmospheric or vacuum tower bottoms are cracked at moderate temperatures to increase production of distillate products and reduce the viscosity of the distillation residues.