ASSESSMENT OF EMISSIONS OF GREENHOUSE GASES FROM FUEL CELL VEHICLES

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EXECUTIVE SUMMARY

Under the Kyoto Protocol, Canada committed to reduce GHG emissions by 6% from 1990 levels by the period 2008 to 2012. Most of the other industrialized countries of the world made similar commitments, although the exact percentage reduction varies from country to country. In most industrial nations transportation represents the single largest source of GHG emissions, in Canada's case accounting for 27 per cent of the total and 26 per cent in the United States. 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 in Canada 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.

It is clear that the transportation sector has a significant role to play in helping Canada and the United States meet their objectives under the Kyoto Protocol. One strategy that holds promise is the development and commercialization of Fuel Cell Vehicles (FCV).

A number of studies have been performed on the GHG emissions of transportation systems. Not all of these studies consider FCV and the full range of fuels for FCV that are potentially viable. The studies use different assumptions making it difficult to compare one study to another. Most of the studies are written from the perspective of the United States and since Canada has a different mix of energy sources than the US it is not clear that the results from US studies are directly applicable to Canada or other nations. The primary intent of this report is to cover most of the fuels currently being considered for FCV and to determine the GHG emissions in the Canadian context. The model being used to calculate GHG's is capable of calculating emissions in Canada and the United States so the results for the United States are also presented. There is some discussion of the likely results in Japan and Europe based on the carbon intensity of their electricity generating sectors.

The results that are obtained from full cycle emissions models are highly dependent on the assumptions that are modeled. This explains why very different results and conclusions are sometimes found in the literature. The philosophy used for this study is that for new fuels and vehicles the best technology commercially available in the year 2010 is modeled. In the case of existing fuels such as gasoline the anticipated improvements applied to the existing emissions are modeled. This approach requires some judgement and care has been taken to treat all fuels the same in terms of projected improvements.

The following table presents the GHG emission reduction potential for each of the primary fuel options in Canada and the United States compared to an equivalent vehicle with an internal combustion engine operated on 30 ppm sulphur gasoline. It is interesting to note the differences in both the absolute value of the reductions and the ranking of the fuel options between the two countries. The reasons for the variances are many but the primary difference is the difference in the carbon intensity of the electricity generation between the two countries.

Table ES-1 Greenhouse Gas Reductions in 2010

Fuel	Source	% Reduction in Canada	Fuel	Source	% Reduction in the US
CH_2	Natural Gas SMR	51.8	CH_2	Natural Gas	44.5
LH_2	Natural Gas	44.3	Methanol	Natural Gas	41.7
Methanol	Natural Gas	43.5	Sulphur Free Gasoline	Crude Oil	25.8
Sulphur Free Gasoline	Crude Oil	27.5	LH_2	Natural Gas	22.5
CH_2	Natural Gas POX	25.0	FT Distillate	Natural Gas	21.9
FT Distillate	Natural Gas	22.5	CH_2	Natural Gas to Electricity	13.8
CH_2	Natural Gas to Electricity	15.5	CH_2	Natural Gas POX	8.5

Electrolytic hydrogen from the existing national mixes of electricity is not a viable option for the future since new electricity generating capacity will have a different mix than the existing generating capacity. The incremental source of electricity in both countries is primarily high efficiency natural gas fired facilities, thus that option is presented in the table.

In both countries the lowest greenhouse gases are derived from decentralized steam methane reforming of hydrogen at a service station site. There are concerns regarding the practicality of decentralized hydrogen from SMR. The plants are relatively large, some require skilled operators, steam generators, cooling water and there may be zoning issues with installing them on service station sites. Early demonstrations of hydrogen powered FCV have used liquid hydrogen or electrolytic hydrogen followed by onboard storage of compressed hydrogen. Liquid hydrogen is heavily dependent on electricity and this can significantly reduce the benefit of the natural gas to liquid hydrogen option as seen in the case for the US.

The use of partial oxidation reformers may be better suited for small decentralized facilities due to their low cost, ease of operation and their size, but the projected reductions in GHG emissions from this option are only 25% in Canada, half of that projected for steam methane reforming facilities. The situation in the US is even less favorable with only an 8.5% reduction in GHG projected. Methanol fueled vehicles will provide a greater reduction in GHG emissions than hydrogen produced from POX reformers.

A number of sensitivity cases and alternative scenarios are examined as well as the main cases. These include reductions in the upstream emissions of natural gas gathering systems, remote methanol and FT distillate facilities using low cost stranded gas reserves, liquid natural gas for countries without gas reserves and high efficiency liquid hydrogen and GTL plants.

Remote methanol facilities are projected to have similar emissions to plants located in Canada or the United States. The extra transportation distances involve more efficient ocean transport and less relatively inefficient rail transport so that overall GHG emissions are little changed from the base case. The use of flared gas from these remote locations was not considered. The GHG credit associated with this gas is substantial and potentially can offset most of the emissions associated with a remote processing facility. It should be noted that approximately two thirds of the world's gas reserves could be classified as remote.

Some countries rely on the importation of Liquefied Natural Gas for their domestic natural gas requirements. In those countries the greatest GHG reductions are derived from the methanol fueled FCV. The additional energy requirements to liquefy the gas outweigh the benefits of steam methane reforming natural gas to hydrogen.

The use of either sulphur free gasoline or Fischer Tropsch fuels provides only about one half of the greenhouse gas benefits of steam methane reformed hydrogen or methanol. While improvements in the production efficiency of these gas to liquids processes are probable in the longer term, due to a number of factors such as their carbon to hydrogen ratio, they are not likely to reach the greenhouse gas emission reduction potential of the other liquid fuel studied, methanol.

Fuel Cell Vehicles offer the potential for very significant reductions in greenhouse gas emissions compared to the gasoline powered internal combustion engine driven vehicle. The choice of fuel for the fuel cell can significantly impact on the GHG benefit received. The magnitude of the reduction is dependent on the specific fuel production parameters and is also country specific. In some countries such as Canada, natural gas to hydrogen via steam methane reforming offers the greatest theoretical reductions in GHG emissions, however if the hydrogen is produced using POX technology rather than SMR half of the GHG reduction is lost. In countries without pipeline natural gas, methanol derived from natural gas will give the greatest reduction. Of the liquid fuels studied the greatest reductions in GHG are from methanol. Natural gas to methanol offers the most consistent reduction of GHG emissions for the various production scenarios and countries examined.

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BTU	British Thermal Units Energy. To convert to kJ multiply BTU by 1.055
CH_4	Methane
CH_2	Compressed Hydrogen
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.
FCV	Fuel Cell Vehicles
FT	Fischer Tropsch
g	Gram
gal	US gallon (3.785 L)
GHG	Greenhouse gases
GJ	Gigajoule (10^9 Joules)
GTL	Gas to Liquids
GWP	Global warming potential over a 100 year period: CO_2, 1; CH_4, 21; N_2O, 310
H_2	Hydrogen
HHV	Higher heating value of a fuel (combustion moisture as liquid)
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
k	Prefix for thousand
km	Kilometre
kWh	Kilowatt-hour
L or l	Litre
LH_2	Liquid Hydrogen
lb	Pound (0.4536 kg)
M	Prefix for million, when used with metric unit
m^3	Cubic metre, 1000 litres
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
PM	Particulate matter
POX	Partial Oxidation Reformer
ppm	Parts per million by volume
S	Sulphur
SCF	Standard Cubic Feet (60F, 14.7 psia)
SFG	Sulphur Free Gasoline
SMR	Steam Methane Reformer
t	Tonne (1000 kg)
THC	Total hydrocarbon
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USG	United States Gallon
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. Most of the other industrialized countries of the world made similar commitments, although the exact percentage reduction varies from country to country. In most industrial nations transportation represents the single largest source of GHG emissions, in Canada's case 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 in Canada 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). Table 1-1 summarizes transportation GHG emissions for 1997 (UNFCCC 1997 database).

Table 1-1 Transportation GHG Emissions for 1997

	Emissions Mt	Emissions CO_2 equivalent Mt	Percent of Canadian Totals
Carbon Dioxide	174,000	174,000	33.5
Methane	25	525	0.58
Nitrous Oxide	29	8990	13.8
Total		183,515	27.1

It is clear that the transportation sector has a significant role to play in helping Canada meet its objectives under the Kyoto Protocol. One strategy that holds promise is the development and commercialization of Fuel Cell Vehicles (FCV).

A number of studies have been performed on the GHG emissions of transportation systems. Not all of these studies consider FCV and the full range of fuels for FCV that are potentially viable. The studies use different assumptions making it difficult to compare one study to another. Most of the studies are written from the perspective of the United States and since Canada has a different mix of energy sources than the US it is not clear that the results from US studies are directly applicable to Canada or other nations. The primary intent of this report is to cover most of the fuels currently being considered for FCV and to determine the GHG emissions in the Canadian context. The model being used to calculate GHG's is capable of calculating emissions in Canada and the United States so the results for the United States are also presented as a sensitivity case. There will be some discussion of the likely results in Japan and Europe based on the carbon intensity of their electricity generating sectors.

Typically, about 72% of greenhouse gas emissions arising from a gasoline-fueled 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 proportionately from fuel manufacturing and delivery for a given type of fuel/vehicle system so that these percentages do not change significantly from changes in gasoline vehicle technology. 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 the following types of emission sources need to be considered:

- Production of the raw energy source;
- Transportation of the energy to a refinery or production plant;
- Conversion of the energy to a fuel for use in an internal combustion or fuel cell engine;
- Transportation of the fuel to a retail site;
- Fuel storage and distribution;
- Vehicle operation;
- Vehicle assembly and transport, and;
- Materials used in the vehicle.

The discussion of the options considered in this report will be grouped by primary energy source (oil, natural gas, and electricity). Within each pathway the discussion will cover the upstream energy production stages, the energy conversion stage where the energy source is converted into a useful fuel and the vehicle operation stage where the fuel is consumed.

1.2 OVERVIEW OF PREVIOUS STUDIES

Wang (1999) provides an excellent overview of the history of the development of fuel cycle emissions and energy use studies. The first studies were reported by Delucchi in 1991 and 1993. These studies have been widely cited in the literature. These studies used an early version of the model used for this study. Delucchi's early work did not consider fuel cell vehicles and did not consider all of the various hydrogen options and Fischer Tropsch fuels looked at here. The other studies cited by Wang and their key points are shown in Table 1-2.

Table 1-2 Previous Studies of Transportation Greenhouse Gas Emissions

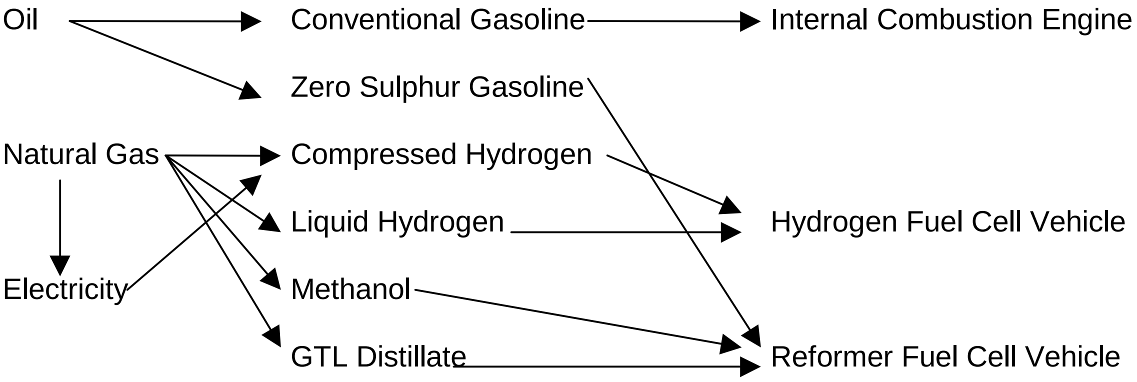
Authors	Date	Key Points
Delucchi	1991,1993	First Studies. No Fuel Cell Vehicles. Limited Fuel Options
NREL	1991,1992	Cellulosic ethanol and reformulated gasoline only. No fuel cell vehicles
Bently	1992	Idaho National Lab. Some fuel cell vehicles. Limited fuel choices. Limited data from upstream stages.
Brogan and Venkateswaran	1992	19 propulsion system-fuel choices studied including FCV. Limited upstream data used. Incomplete fuel cycles.
Ecotraffic	1992	Results for Sweden. No FCV. Only 5% of electricity is generated from carbon based fuels gives very different results than US studies.
Wang and Santini	1993	Electric and gasoline vehicles only for 4 US cities.
Darrow	1994	No fuel cell vehicles. Electric vehicles, CNG and other alternative fuels. US and California data.
Acurex	1996	California focus. No FCV. GHG and criteria emissions considered.
Delucchi	1997	Update of earlier work. No FCV. Additional fuels and fuel options, eg compressed or liquid hydrogen, centralized or decentralized options.
Argonne	1998	Electric vehicle focussed.
Sheehan	1998	Biodiesel only
Wang	1999	Greet 1.5. Includes FCV. Wide range of Fuel Options
Levelton	1999	Application of Delucchi model to Canada. Updated to include FCV

Wang concluded that the work by Delucchi and Acurex was the most comprehensive in terms of fuels and vehicle technologies. Delucchi established the spreadsheet model approach to full cycle emissions analyses.

1.3 SCOPE OF WORK

This study compares the full cycle emissions of seven energy pathways to power a fuel cell vehicle to that of the conventional oil to gasoline for the internal combustion engine pathway. The pathways are shown in Figure 1-1. Four pathways involve the off board production of hydrogen, natural gas to compressed or liquid hydrogen, liquid natural gas to compressed hydrogen, and natural gas to electricity to compressed hydrogen and three involve the on board generation of hydrogen from methanol, zero sulphur gasoline and from Fischer Tropsch naphtha or distillate. The study also investigates the sensitivity of the results to some of the key input variables for each of the three stages in the full cycle. The later data is useful to understand the relative importance of the stages in the cycle, the degree of uncertainty of some of the processes, in how technologies may develop over time, and where research efforts may offer the biggest rewards.

Figure 1-1 Energy Pathways for Fuel Cell Vehicles.



2. GENERAL APPROACH AND METHODOLOGY

2.1 OVERALL APPROACH USED FOR THE STUDY

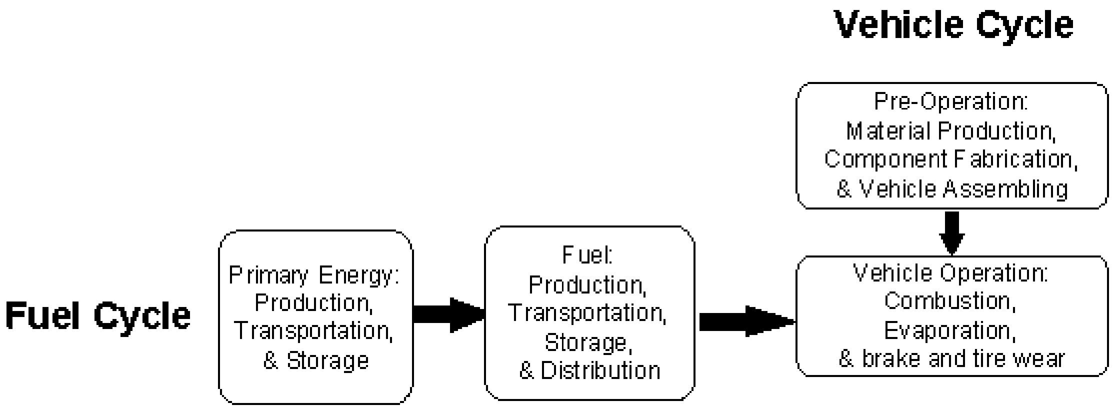
The objectives of the study require the development of reliable estimates of the energy use and greenhouse gas emissions associated with production and use of gasoline and fuels used in fuel cell vehicles. Given the developing nature of FCV the year 2010 was chosen as the time of comparison. This recognizes that existing FCV are pre-production prototypes that require further development. The technology for some of the fuel production options is developing rapidly as well. With this information, the net effect on energy consumption and greenhouse gas emissions of fuel cell vehicles can be determined.

Lifecycle energy use and greenhouse gas emissions for gasoline in Canada are the references for comparison in this study. All stages were considered 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 average Canadian refinery and the average for crude oil produced in Canada. The differences between Canada and the United States are discussed along with the likely impact in other regions such as Japan and Europe. The methods used for the analysis are discussed later in this chapter.

2.2 OVERVIEW OF FULL CYCLE CONCEPT FOR GASOLINE AND ALTERNATIVE FUELS

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. Since most of the vehicles considered here are Fuel Cell Vehicles this extra step does not significantly change the results. 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



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, and 1998), the other by Wang (1996, 1999). The work of Delucchi in the 1987-1993 period resulted in the development of a spreadsheet model based on Lotus software for Apple^{TM} 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 some of 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, 1999) developed a more user-friendly spreadsheet model for the US DOE in Excel^{TM}. This model is available on the Internet at www.ipd.anl.gov/ttrdc/greet/greet1-5.zip.

Delucchi has updated his model since 1993, as described in Delucchi and Lipman (1997) 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 and (S&T)^2 (1999) for NRCan. Levelton and (S&T)^2 has also used it for two studies for Agriculture and AgriFood Canada and (S&T)^2 has used it for a study for the Province of Alberta. 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. More detail on the model is presented in Appendix A.

2.4 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 the Intergovernmental Panel on Climate Change (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 and the IPCC.

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 conventional motor vehicles and the relative efficiency of FCV are important inputs to the analysis. The assumptions made for each of the fuel and vehicle combinations are clearly described in the appropriate section of the report.

The baseline is a conventional gasoline vehicle fuelled by low sulphur (30 ppm) gasoline. The time period under consideration is 2010 when it is expected that FCV will be relatively mature technology. The average 2010 vehicle is expected to have slightly better fuel economy than existing vehicles. Some key baseline information for motor vehicles from NRCan is shown in Table 2-1. The distance travelled and fuel economy data is used in the model.

Table 2-1 Key Baseline Information for Motor Vehicles in Canada

Parameter	1995	2000	2010	2020	1995-2020 ANNUAL GROWTH RATE (%/YR)
Vehicle stock (thousands of vehicles)					
Automobiles	11,349	11,436	12,249	13,964	+ 0.83
Gasoline Trucks	4,231	4,759	6,158	7,703	+ 2.43
Light-Duty Diesel Trucks	310	364	453	505	+1.97
Heavy-Duty Diesel Trucks	210	216	257	315	+1.64
Total (rounded)	16,100	16,780	19,120	22,520	+ 1.35
Average Km Traveled (km/yr)					
Automobiles	21,579	21,721	21,977	22,509	+0.170
Gasoline Trucks	21,229	21,061	21,095	21,364	+0.025
New Vehicle Fuel Economy [1,2]					
Automobiles (L/100km)	8.1	8.0	7.5	6.9	- 0.62
Automobiles (miles/USG)	29.2	29.5	31.5	34.2	- 0.62
Gasoline Trucks (L/100km)	11.2	11.1	10.6	10.0	-0.45
On-Road New Vehicle Fuel Economy					
Automobiles (L/100km)	9.7	9.6	9.0	8.3	- 0.62
Automobiles (miles/USG)	24.3	24.6	26.2	28.5	- 0.62
Gasoline Trucks (L/100km)	13	13.3	12.7	12.0	-0.45
Car Stock Fuel Economy					
Automobiles (L/100km)	10.0	9.7	9.1	8.4	- 0.7
Automobiles (miles/USG)	23.6	24.3	26.0	28.1	- 0.7
Greenhouse Gas Emissions					
Carbon Dioxide(Mt)[3]	108.9	112.6	124.8	140.6	+ 1.03
Methane (kt)[3]	17.1	17.7	19.6	22.0	+ 1.03
N_2O (kt)[3]	44.0	46.0	50.8	57.2	+ 1.03
Total CO_2 Equivalent [4]	122.9	127.2	140.9	158.8	+ 1.03

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[1] Combined city / highway fuel economy based on 0.55 city: 0.45 highway kilometers travelled assumed for the USEPA test procedure

[2] On-Road vehicle fuel economy 1 / 1.2 (Jaques et al, 1997)

[3] Disaggregated from data in NRCAN, 1997 using data in Jaques, et al, 1997

[4] CO2:1; CH4:21; N2O:310

The analysis of fuel cycle emissions utilizes annual distance traveled and vehicle survival statistics to estimate cumulative distance traveled by a typical vehicle and its non-greenhouse gas emissions at the mid-point of its life.[5]

Emissions of regulated pollutants such as carbon monoxide, nitrogen oxides, VOC's, particulates and sulphur oxides can be calculated by the model. For vehicle emissions the methodology used is a modified version of the Mobile 5 model developed by the US EPA. It must be recognized that very little information on these types of emissions is available for FCV at the current time. Ratios of expected emissions for FCV to the projected emissions of 2010 gasoline powered vehicles have been estimated in order to complete the full cycle analyses.

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[5] The annual kilometer accumulation rates and survival fractions used in this study for passenger cars and heavy-duty vehicles were originally provided by NRCan to Levelton (1999).

3. ENERGY PATHWAYS OF INTEREST

Fuel cell vehicles require hydrogen to produce electricity. Hydrogen must be viewed as an energy carrier rather than an energy source. That is, it must be made from another source of energy such as crude oil, natural gas, electricity or perhaps coal or biomass. The energy source considered here are oil, natural gas and electricity from a variety of sources as these are the most likely energy sources to be used in the 2010 time period.

For the conversion of the energy source to hydrogen and the utilization of the hydrogen in a FCV it is assumed that a state of the art facility will be used to make the conversion. This is appropriate given the 2010 time period under consideration and the fact that a significant market penetration of FCV will require new facilities to produce the hydrogen or hydrogen carrier. It has been assumed that there will be continual improvement in energy efficiency for the conventional oil refineries but it is not assumed that new grass roots refineries will be constructed. This comparison of new and old is valid because it is unlikely that new energy efficient refineries will be built to replace the existing facilities.

3.1 OIL BASED PATHWAYS

Two oil based pathways are studied, the baseline case of low sulphur gasoline used in a conventional internal combustion engine and the case where a zero sulphur gasoline is used in a fuel cell vehicle with an onboard reformer. In the later case the fuel is produced in a conventional refinery and could be used in an internal combustion engine.

3.1.1 Crude Oil Production

The production of crude oil requires energy to extract it from the ground and in some cases to upgrade it to a form that can be used in a refinery. There can also be fugitive emissions of methane and carbon dioxide arising from the extraction process. Crude oil production can be classified according to the type of oil produced (light, heavy, bitumen) and according to the process (conventional or oil sands). In Canada, the Canadian Association of Petroleum Producers (CAPP 1998) has inventoried the GHG emissions from oil extraction for the different types of crude oils. That data is summarized in Table 3-1.

Table 3-1 GHG Emissions from Crude Oil Production in Canada

Type	Indirect	CO_2	Methane	Nitrous Oxide	Total
Units	Gms CO_2 eq/M^3	Gms CO_2 eq/M^3	Gms CO_2 eq/M^3	Gms CO_2 eq/M^3	Gms CO_2 eq/M^3
Conventional		150,730	49,870	1,460	202,060
Heavy Oil	260,620	80,490	373,750	270	715,130
Bitumen		450,240	25,710	2,500	478,450
Oil Sands	17,370	677,400	38,820	7,840	741,430
Weighted Average	55,310	241,200	126,530	2,320	425,360

The indirect emissions are the result of purchased electricity used in the extraction process. It is obvious from the table that there is considerable variation in emissions between the types of crude oil that can be processed to produce gasoline. Emissions in Canada have a tendency to be higher than in some other countries due to the greater proportion of heavy oil and oil sand derived crude oil produced here. The US emissions for crude oil production that are included in the model are about 195,000 gms CO_2 eq/M^3. This is very similar to the Canadian conventional oil values. Higher emissions from the transportation of imported oil and higher emissions in the refineries due to more complex processing offset this lower US crude oil production value.

Oil producers are working hard to reduce emissions. The oil sands producers in particular have plans to reduce emissions substantially from these 1995 levels. At the same time there is a great expansion underway in the oil sand and heavy oil sectors so it is not expected that significant changes in the average emissions will occur in the near future.

The model has been calibrated to represent the volumetric weighted average emissions for Canadian crude oil production. This is a conservative approach as it could be argued that FCV will displace the marginal source of crude oil which is likely to be tar sands synthetic crude oil. This oil has the highest GHG emission rate 75% higher than the average emission rate.

The distribution emissions for crude oil are based on the average pipeline emissions resulting from the movement of the crude from the field to refineries across Canada. No imported crude oil is included in the Canadian results.

3.1.2 Gasoline

The energy and type of energy used to make gasoline in Canadian refineries was extracted from the Foundation Paper for the Downstream Petroleum Industry, (Purvin & Gertz 1999) and from published Canadian Refining Industry averages (Nyboer). Interviews with Canadian refiners provided insight into expected energy efficiency improvements in the refineries over the next decade and this was incorporated in the model.

The energy consumed in the refinery has been allocated to the individual products based on estimates of the energy used in each processing unit.

Canadian refiners use less energy to produce gasoline than American refiners. The positive variances are due to lower gasoline production per barrel of oil in Canadian facilities, thus requiring less intensive refining. The use of some octane additives in Canada also lessens energy consumption. These are only partially offset by generally larger, more efficient refineries in the US.

The industry does have some options for reducing energy consumption below the levels projected here depending on the processes chosen to reduce sulphur levels. New unproven processes are available but most will not be proven until after the industry needs to make its investment decisions to meet Canadian standards for 2002 and 2005.

3.1.3 Low Sulphur (30 ppm) Gasoline

Low sulphur (30 ppm) gasoline will be required in Canada and the United States starting in 2005 and it is assumed that it will still be the requirement in 2010. This gasoline will enable vehicle catalytic converters to operate at maximum efficiency over the life of the unit and will result in lower N_2O emissions from the vehicle compared to today's cars and fuels. This lower emission rate is factored into the full cycle emission data.

The Foundation Paper was used to verify the incremental refinery energy use in 2010 when low sulphur (30 ppm sulphur) gasoline will be required. This estimate is based on conventional hydrotreating technologies and replacing the lost octane that these processes cause. There are newer processes being developed that use less energy, they have not yet been commercially demonstrated.

The emissions for the storage and distribution of gasoline are based on the typical Canadian distribution system with a combination of pipeline, rail and truck used to move the product from refineries to service stations.

The greenhouse emissions for the production and distribution of low sulphur gasoline are shown in Table 3-2.

3.1.4 Sulphur Free Gasoline

Sulphur free gasoline will be extremely difficult to produce and distribute without being contaminated with some sulphur. The industry is now suggesting that sulphur free gasoline may contain 5 to 10 ppm of sulphur to allow for the inevitable contamination of the fuel through the distribution network. Within the refinery it will still be necessary to produce a product with very close to zero sulphur. This will require more energy and a higher cost compared to the 30 ppm level that will be commercialized by 2005.

There is very little data available on producing this very low sulphur gasoline. A recent analysis by MathPro Inc. for the Alliance of Automobile Manufacturers investigated the process requirements, the costs, and included estimates of the extra energy required to achieve 5 ppm gasoline. It was determined that a multitude of measures will be required including increasing the severity and scope of FCC naphtha desulphurization, desulphurizing other refinery streams and applying best practices in refining operations to control the sulphur content of other refinery streams. The analysis only considered the new low energy processes under development. There was a requirement for about 10% more energy to achieve 5 ppm compared to 30 ppm sulphur. For the purposes of this analysis it will be assumed that there is an energy requirement of 10% more than the 30 ppm case. It should be noted that this sulphur free gasoline is still likely to require a sulphur trap on the FCV.

The emissions for the production of crude oil, refining of gasoline and distribution of the fuel to a service station are shown in Table 3-2 for both low and zero sulphur gasolines.

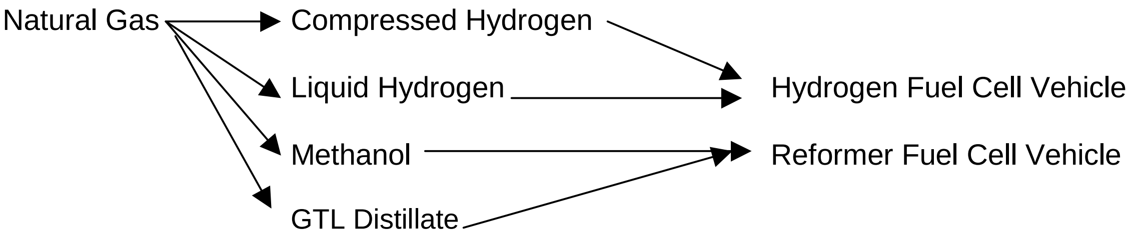
Table 3-2 Greenhouse Gas Emissions for Low and Sulphur Free Gasoline

Stage	30 ppm S Gasoline	Sulphur Free Gasoline
	Emissions	Emissions
Units	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed
Fuel Dispensing	162	156
Fuel Distribution and Storage	1,212	1,196
Fuel Production	12,733	13,848
Feedstock Transmission	206	206
Feedstock Recovery	8,880	8,877
Gas Leaks and Flares	2,677	2,677
Total	25,871	26,960

3.2 NATURAL GAS PATHWAYS

There are four natural gas pathways considered here. Natural gas can be reformed to make hydrogen, which can be compressed or liquefied and then used in a FCV, or the natural gas can be converted to methanol or naphtha/distillate via a Gas to Liquids process, the methanol or naphtha is then reformed to hydrogen on board a vehicle. The pathways are shown in Figure 3-1. The full cycle emissions for each of these pathways is considered in the following sections.

Figure 3-1 Natural Gas Pathways



3.2.1 Natural Gas Production

Natural gas supplies a significant portion of Canada's and the world's energy requirements. It can be used directly as a fuel or as feedstock for fuels such as methanol and hydrogen. It has the lowest carbon content of any fossil fuel and thus has the potential to reduce greenhouse gas emissions compared to other fossil fuels. Natural gas reserves are abundant and distributed throughout the world. There is also a significant amount of natural gas in the world that is vented or flared because it is remote from markets. There is the potential to capture this gas, convert it to methanol, hydrogen or GTL's and use the fuel for fuel cell vehicles. The potential impact of the use of this stranded gas is discussed in the sensitivity section of the report.

The natural gas industry in Canada has inventoried the emissions of greenhouse gases that arise from the production, processing, transmission, distribution and use of natural gas (CGA 1997 and Radian 1997). This industry data for 1995 is summarized in Table 3-3. The data has been used as inputs to the model for all natural gas based processes. The production, processing, transmission and storage emissions are attributed to all of the marketable gas produced in Canada and the distribution emissions are attributed to the gas sold in Canada.

Table 3-3 GHG Emissions from Natural Gas in Canada

	Carbon Dioxide	Methane	Nitrous Oxides	CO_2 Equivalents	% of Total
Units	Kilotonnes	Kilotonnes	Kilotonnes	Kilotonnes	
Production	3,879	607	0.8108	16,877	29.4
Processing	18,038	115	1.0004	20,763	36.2
Transmission	10,560	271	0.6002	16,437	28.7
Storage	63	6.9	0.0158	213	0.4
Distribution	95	141	0.0008	3,056	5.3
Total	32,635	1,140	2.43	57,347	100.0
% of Total	56.9	41.7	1.3	100.0	

The industry has an active program in place to reduce GHG emissions. Emissions of methane as a function of marketable gas have been declining through the 1990's and compare favourably with US emission rates. It has been assumed that methane leakage rates will decline from these 1995 levels at 0.5% per year for processing, storage and transmission stages and at 1% per year for the other stages. This is being accomplished by the implementation of no-bleed pneumatic devices, turbine compressor engines, plastic pipe instead of steel and cast iron distribution mains and by increased utilization of existing mains where losses are a function of the system configuration and not the throughput.

3.2.2 Hydrogen

The conversion of natural gas to hydrogen is a well-established commercial process. The conversion is generally carried out by a process known as steam methane reforming (SMR). The commercial plants are usually fairly large with a capacity of two to 50 tonnes per day (0.8 to 20 million SCF per day). For some niche applications units as small as a few hundred kilograms of hydrogen a day can be economic. The use of alternative technology known as partial oxidation (POX) will be investigated as a sensitivity case.

Two concepts are evaluated. The first involves the onsite generation of compressed hydrogen at a service station and the second is a central facility for the production of liquid hydrogen which is then transported to a local service station. These concepts are considered to be the most likely scenarios for the development of a hydrogen fuel infrastructure.

It is beyond the scope of this report to consider the feasibility of the options being considered but it must be noted that the production of hydrogen by a SMR plant located at a service station is a very different concept to the modern service station. The SMR plant is quite large, although some manufacturers offer skid mounted units, and may not fit on many sites. There will be zoning issues in many jurisdictions as the plants are more of a chemical manufacturing facility, utilizing steam, high process pressures and temperatures, than a fuel retailer. Some manufacturers require skilled operators but others offer unattended operations. The technology offers the highest efficiency and is included in most other studies so it is included here.

3.2.2.1 Compressed Hydrogen

The average Canadian urban service station will sell 5 million litres of gasoline per year. This station supplies the needs of about 2500 vehicles. If a hydrogen system is sized to meet the equivalent energy demand and consideration is given to the higher efficiency of a FCV then there will be a requirement for approximately 2000 kg of hydrogen per day. This is equivalent to 800,000 SCF per day of hydrogen. This assumes that all of the vehicles using this station use hydrogen. This may not be a reasonable scenario in the early years of introduction of FCV so in the sensitivity section of the report the impact of smaller hydrogen production facilities will be studied.

There is some loss of efficiency when plants of this size are produced. The energy requirements for SMR plants of this size are shown in Table 3-4.

Table 3-4 Energy Requirements for Small Scale SMR Plants

Vendor	Natural Gas Used	Electrical Power	Source
	SCF/million BTU H_2	KWh/million BTU H_2	
Caloric	1445	2.3	www.caloric.de
Mahler	1500	2.7	Company brochure
Praxair	1400	29[6]	Thomas et al.
BOC	1260	12.7[5]	Thomas et al.

The specific case modeled will be 1450 SCF of natural gas (1000 BTU/SCF) and 2.5 kWh of electricity plus the electricity for compression per million BTU of hydrogen. It is assumed that this will improve by 0.20% per year between the base year of 1996 and 2010 and that in the year 2010 the gas consumption will be 1387 SCF/million BTU. The system efficiency in 1996 is 68% and it will improve by 2010 to be 69.9%.

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[6] Includes compression energy.

It is assumed that electricity will be used to drive the hydrogen compressors at the service station site and that the storage pressure will be 5000 psi. The greenhouse gas emissions for the production and compression of hydrogen are shown in Table 3-5.

Table 3-5 Greenhouse Gas Emissions for Compressed Hydrogen

Stage	Emissions
Units	Gms CO_2 / million BTU dispensed
Fuel Dispensing	4,580
Fuel Distribution and Storage	296
Fuel Production	75,611
Feedstock Transmission	3,365
Feedstock Recovery	5,604
Gas Leaks and Flares	5,836
CO_2 from Natural Gas	955
Total	96,246

3.2.2.2 Liquid Hydrogen

Liquid hydrogen has a density 790 times that of gaseous hydrogen and 3.1 times that of hydrogen compressed to 5000 psi. The higher density results in lower distribution costs and may make off site hydrogen production an attractive option for the refueling infrastructure.

The concept of a large SMR facility producing liquid hydrogen which is then distributed by truck to local service stations is one that is often described for the refueling infrastructure for hydrogen powered FCV's. Large SMR can be more efficient than smaller units that would located on site due to the scale of the units and the potential to recover and reuse some of the surplus energy generated by such units. However, the liquefaction process is relatively inefficient and requires substantial electrical energy.

Liquefaction plants sizes have been reduced over the past fifty years. In the 1950's plants typically had capacities of 25 to 60 t/d. There are about 10 medium sized plants in operation around the world with capacities of as small as 10 t/day. Recently, small-scale plants with capacity of 3-12 t/d have been built in the US, Japan and Europe.

The natural gas requirements in very large plants can be as low as 1250 SCF/million BTU of hydrogen produced (Linde). Thomas reported gas requirements for plants ranging is size from 26.7 t/d to 327 t/d. In general gas consumption decreased with increasing plant size, with the smaller plants needing 1470 SCF/million BTU and the largest plant using 1365 SCF/million BTU.

The base case modeled will be a 26.7 t/d plant currently consuming 1378 SCF/million BTU of hydrogen. The same 0.2% efficiency improvement rate used for smaller plants will be applied between 1996 and 2010. The gas consumption in 2010 will be 1350 SCF/million BTU of hydrogen. The liquid hydrogen will be transported by truck an average distance of 500 km to reflect the likely early introduction, low market penetration scenario. Fuel boil off and leakage is a problem with all cryogenic fuels. It has been assumed that in 2010 1.3% of the hydrogen is lost due to leakage and boil off at each of the three transfer stages in this scenario. This is the same case modeled by Delucchi in his work. A sensitivity case will be run with a larger more efficient plant and shorter transportation distances to reflect the case of very significant market penetration.

The energy required for liquefaction will be supplied by electricity. Wurster (1994) reports electrical consumption of 13 kW/kg of hydrogen equivalent to an efficiency of 69%. Wurster reports on long term technology developments that may reduce this to 9 kW/kg (79% efficiency) by 2020 and perhaps as low as 5 kW/kg (88% efficiency) by 2050. Wang (2000) reports an efficiency of 65% for current technology and 70% for future applications. Delucchi reports efficiencies of 74% for large central facilities and 67% for small remote locations. Wurster's data for existing technology (69% efficiency) will be modeled here. Note that Wang's estimate for future technology is only 70%. The greenhouse gas emissions for the production of liquid hydrogen are shown in Table 3-6.

Table 3-6 Greenhouse Gas Emissions for Liquid Hydrogen

Stage	Emissions
Units	Gms CO_2 / million BTU dispensed
Fuel Dispensing	22,758
Fuel Distribution and Storage	801
Fuel Production	74,491
Feedstock Transmission	3,339
Feedstock Recovery	5,560
Gas Leaks and Flares	5,860
CO_2 from Natural Gas	947
Total	113,757

Greenhouse gas emissions for liquid hydrogen applications are about 18% higher than the emissions for compressed hydrogen due to the extra energy required for liquefaction.

3.2.3 Methanol

The production of methanol from natural gas is practiced around the world. The technology is well known and most existing facilities use a version of steam methane reforming. There are about ten process licensors offering process packages. Some of these licensors offer alternative designs such as autothermal or combined reforming and some of these new designs are starting to make inroads into the market. There is a considerable renewal effort underway in the methanol industry. Small, old inefficient plants are being closed and replaced with large, efficient lower cost facilities. This rapid, continual improvement in a competitive industry accounts for much of the variation concerning methanol plant efficiencies found in the literature.

The efficiency of the methanol conversion process has a large impact on the greenhouse gas emissions produced. Existing SMR methanol plants consume about 100 SCF (35.8 GJ/t)(63.3% efficiency HHV) of natural gas per USG of methanol produced. New combined reforming facilities can reduce gas consumption to 30.0-31.2 GJ/t (84-88 SCF per USG)(72.5-75% energy efficiency HHV)(Lurgi, 1997). The basis for the modeling will be 31.8 GJ/t in the year 2000, improving at the rate of 0.2% per year to the year 2010. The gas requirement in 2010 will be 31.2 GJ/t. The plant is assumed to produce its own electricity and the energy for that is included in the gas consumption.

Methanol is produced in large plants. This means that a few plants could supply the methanol requirements of many FCV's. The distribution of methanol may involve water transport, depending on where the plant is built, as well as rail and truck transport. The base case modeled here assumes that the methanol moves 1700 miles by rail and 75 miles by truck. The 1700 miles is the current weighted average rail distance that product moves from the Methanex plant in Medicine Hat to Canadian customers. This puts the methanol plant very close to the source of gas and it is assumed that the relative distance for the transmission of the feedstock is 12% of the average transmission distance for other gas uses such as hydrogen plants, commercial and residential applications. The impact of alternative distribution scenarios will be investigated in the sensitivity of the report. With a large enough demand for methanol it is possible that it could be moved by pipeline which is more energy efficient than rail movements. The greenhouse gas emissions and the impact of gas consumption on those emissions is shown in Table 3-7.

Table 3-7 Greenhouse Gas Emissions for Methanol

	Emissions	Emissions	Emissions
Gas Consumption	35.8 GJ/tonne	31.8 GJ/tonne	31.2 GJ/tonne
	SMR Today	Combined Reforming Today	Combined Reforming 2010
Units	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed
Fuel Dispensing	279	279	279
Fuel Distribution and Storage	5,655	5,655	5,655
Fuel Production	18,185	10,229	9,049
Feedstock Transmission	442	399	393
Feedstock Recovery	6,110	5,516	5,429
Gas Leaks and Flares	3,371	3,045	2,995
CO_2 from Natural Gas	1,041	940	925
Total	35,083	26,063	24,725

3.2.4 Gas to Liquids

The need for fuels with essentially no sulphur has resulted in some interest in naphtha and distillates from gas to liquids processes being considered for FCV. Gas to liquids processes are commercially operated by Sasol and Shell in South Africa and Malaysia respectively. The processes are seen by some as an attractive way to commercialize stranded gas resources. There are a number of process developers offering processes that produce a variety of products. The processes all involve the production of synthesis gas and the conversion of gas to liquid paraffinic products that are a function of the catalysts used.

The energy requirements of the processes can vary depending on the process vendor. Wang (1999b) summarized the efficiency of some of the GTL processes. That information is summarized in Table 3-8.

Table 3-8 Energy Efficiencies of Various GTL Proposals

Source	Energy Efficiency	Comments
Marshall	55	A POX reformer with a small SMR reformer.
	62	Designs by Sasol, Shell and Exxon
	57	Syntroleum technology
Russell	66	Syntroleum technology with a steam co-product.
	49	Syntroleum technology with no demand for steam.
Choi	46	Shell design. Small plant. No co-product energy.
	61	Shell design. Small plant. Electricity co-product.
Choi	57	Shell design. Large plant. No co-product.
	58	Shell design. Large plant. Electricity co-product.
Wang’s base case	66	Syntroleum design. Steam and Electricity co-products.
	49	Syntroleum design. No co-products.
	57	Shell design. No co-products.
	61.5	50% Syntroleum plants and 50% Shell plants.

For ease of comparison it will be assumed that the GTL plant is located in Canada and has the same distribution scenario as a methanol plant. The case of a remote facility will be covered as a sensitivity case.

A Syntroleum type process is modeled here as Syntroleum is one of the most active process developers and has announced plans for a 10,000 bbl/day commercial plant. The gas requirements for this process are 10,000 SCF/bbl of product and a net 50 kW of electricity is available for export. This gas requirement and electricity output is often quoted in the literature (Gradassi, Agee). This case represents a current efficiency of 55.2%. There is no credit assumed for steam that may be produced in addition to the fuel and electricity as it is low quality and may be difficult to market. It is assumed that improvements will happen at the relatively rapid rate of 0.5% per year and that by 2010 gas requirements will be 9200 SCF/bbl and an efficiency of over 58%. The greenhouse gas emissions are presented in Table 3-9. Sensitivity to gas use will be studied in the sensitivity section since Gradassi reports values from 8,000 to 11,400 SCF/bbl. The electricity that is produced will replace electricity generated by natural gas, as that is the marginal source of electricity for most regions of Canada. The product distribution distances are the same as assumed for methanol.

Table 3-9 Greenhouse Gas Emissions for GTL's.

Stage	Emissions
Units	Gms CO_2 / million BTU dispensed
Fuel Dispensing	124
Fuel Distribution and Storage	2,681
Fuel Production	21,654
Feedstock Transmission	488
Feedstock Recovery	6,731
Gas Leaks and Flares	3,713
CO_2 from Natural Gas	1,147
Co-product electricity	-446
Total	36,091

These emissions are approximately 35% higher than the emissions for the production of sulphur free gasoline as described in section 3.1.4. A case could be made that GTL's will compete against the marginal sources of crude oil. In Canada that would be oil sands derived crude. If the sulphur free gasoline was manufactured from oil sands synthetic crude rather than the average crude types in Canada those emissions would be approximately 34,000 gms CO_2 / million BTU dispensed based on today's practices. This is almost as high as GTL processes but oil sands developers are making process modifications to reduce their emissions of GHGs and it is anticipated that by 2010 emissions may be as low as 30,000 gms CO_2 / million BTU dispensed.

3.3 ELECTRICITY PATHWAYS

Electricity is not a pathway in the same manner as oil or natural gas since the electricity must be produced from a primary energy source such as oil, natural gas, nuclear, coal or hydro. Electrolytic hydrogen is of interest because electrolysis units are capable of rapid start up and shut down and thus may be better suited to hydrogen production for fluctuating loads such as would be found at a service station.

Ideally the electricity would be produced from non-carbon sources such as hydro or nuclear. This would produce the lowest greenhouse gas emissions. In practice the two scenarios that would be logical to analyze are electricity from the average mix of electricity sources and electricity produced from natural gas in high efficiency gas turbines since natural gas is the marginal source of electricity is many parts of Canada. It is assumed that these facilities have an efficiency of 50%. The national mix is only appropriate if a very low penetration of FCV is assumed such that there is very little additional demand for electricity. Since most of the other alternatives examined assumed significant vehicle sales requiring new facilities it will be assumed that the electricity will come from natural gas. The results from the national mix of electricity are shown for comparison to the electricity from natural gas option only.

In Table 3-10 the GHG emissions for each source of electricity are shown for Canada. Also shown is the Canadian national mix of sources, the US national mix and an estimate of emissions for Japan and Western Europe based on the electricity mix in each of those regions and the US emission factors for each energy source (coal, oil, nuclear etc.).

Table 3-10 GHG Emissions from Electricity Generation

	GHG Emissions
Units	Gms CO_2 / million BTU electricity
Coal	329,509
Oil	297,038
Gas Boiler	197,328
Gas Turbine	138,639
Nuclear	4,102
Hydro	7,114
Canadian National Electricity Mix	70,505
American National Electricity Mix	214,373
Europe	128,000
Japan	160,000

It can be seen from the table that Canadian and US emissions from electricity generation bracket the emissions from electricity generation in Japan and Europe.

3.3.1 Compressed Hydrogen

Hydrogen can be produced from the electrolysis of water. There are a number of manufacturers producing units that can produce from several kg per day of hydrogen up to tens of tonnes per day. Electrolysis units are generally more cost competitive than SMR units at the very small sizes. For that reason only compressed hydrogen will be analyzed.

The energy consumption for hydrogen production by electrolysis is reported to be 50 kWh/kg hydrogen (Thomas). This corresponds to an efficiency of 78.8%. It will be assumed that small improvements in efficiency will be made and that by 2010 the efficiency will be 81.0%. It will be assumed that the compression energy will be the same as for a SMR on site facility. The GHG emissions for the two sources of electricity, the current national mix of generating sources and the production of electricity from natural gas for hydrogen production are shown in Table 3-11.

Table 3-11 Greenhouse Gas Emissions for Electrolytic Hydrogen

Stage	National Electricity Mix	Natural Gas to Electricity
	Emissions	Emissions
Units	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed
Fuel Dispensing	4,580	9,006
Fuel Distribution and Storage	296	296
Fuel Production	87,274	171,612
Feedstock Transmission	0	0
Feedstock Recovery	0	0
Gas Leaks and Flares	0	0
Total	92,150	180,914

3.4 SUMMARY

The greenhouse gas emissions for the base cases of the upstream fuel cycles are shown in Table 3-12. Care must be taken when comparing the emissions since the hydrogen options have no carbon in the fuel while the other options will release carbon dioxide on board the vehicles. To assist with the comparison the carbon imbedded in the hydrocarbon fuels has been added to the table. In addition the fuels have varying hydrogen-generating efficiencies on board the vehicles that will impact on the full cycle emissions. Comparisons between the hydrogen options are valid and informative.

Table 3-12 Comparisons of Upstream Emissions

	30 ppm S Gasoline	Compressed Hydrogen from NG	Liquid Hydrogen from NG	Electrolytic Hydrogen from Natural Gas	Methanol from NG	Sulphur Free Gasoline	GTL
Units	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed
Fuel Dispensing	162	4,580	22,758	9,006	279	156	124
Fuel Distribution and Storage	1,212	296	801	296	5,655	1,196	2,681
Fuel Production	12,733	75,611	74,491	171,612	9,049	13,848	21,654
Feedstock Transmission	206	3,365	3,339	0	393	206	488
Feedstock Recovery	8,880	5,604	5,560	0	5,428	8,877	6,731
Gas Leaks and Flares	2,677	5,836	5,860	0	2,995	2,677	3,713
CO_2 from Natural Gas	0	955	947	0	925	0	1,147
Co-product Credits	0	0	0	0	0	0	-446
Total	25,871	96,246	113,757	180,914	24,725	26,960	36,091
Carbon in Fuel	70,842	0	0	0	63,868	70,842	69,212
Total including Fuel Carbon	96,713	96,246	113,757	180,914	88,593	97,802	105,303

On the basis of the assumptions made for each of the fuel options the lowest fuel cycle greenhouse gas emissions are derived from methanol followed by compressed hydrogen from natural gas at decentralized facilities. In the next section the vehicle is considered and estimates of relative vehicle efficiencies are made.

4. FUEL CELL VEHICLES

Fuel cell vehicles have a number of advantages over vehicles powered by internal combustion engines. They have lower exhaust emissions and a higher efficiency due both to the higher efficiency of the fuel cell compared to the ICE and the torque characteristics of the electric drive system. The efficiency advantage of the fuel cell is particularly large at part load and only modestly higher at full load. Thus, in the real world the relative efficiency of fuel cell vehicles compared to the gasoline powered internal combustion engine is strongly dependent on the vehicle duty cycle. Relative fuel economy ratios of 3 or more are found in the literature (Wang, 1999 and Stodolsky) but these are for mild driving cycles such as the EPA urban test. Real world factors are expected to be lower.

Directed Technologies Inc. (Thomas, 1999) have published a number of papers describing the relative fuel economy of FCV's using different fuels. These are based on a driving simulation model developed by DTI. Results have been published for a number of driving cycles including one designed to mirror the real world fuel economy of vehicles in North America. This DTI data is used as the starting point for developing the relative efficiency of the FCV and fuels considered here.

As the time period for the analyses is 2010 it has been assumed that there will be continued development of FCV. The best case scenarios developed by DTI are the starting point and they are further adjusted for technology developments that have been demonstrated and announced and are beyond the assumptions that DTI made. Real world fuel economy has been used in this modeling so the DTI efficiency factors for the faster urban and highway driving cycles are used as the starting point for determining relative system efficiency.

The Delucchi model calculates the impact of vehicle weight separately from relative engine efficiency. It is thus necessary to determine the impact of the change in powertrain weight and the change in fuel weight separately from the change in engine efficiency. Starting with information published by DTI and the California Air Resources Board the following incremental weight factors for the powertrain have been developed. The model calculates the fuel tank and fuel weight required for the desired vehicle range. The model also uses a weight compounding factor of 1.065 to allow for the extra structure required for the higher powertrain weight. It has been assumed that the gasoline ICE vehicle and all of the FCVs have the same range of 350 miles.

Table 4-1 Incremental Weights of Fuel Cell Vehicles

	Compressed Hydrogen FCV	Methanol FCV	Gasoline FCV
Incremental Powertrain weight, lbs.	0	200	250
Calculated Fuel weight, lbs.	12.2	99	56.9
Calculated Tank weight, lbs.	86	36	23
Total curb weight increment to ICE, lbs.	-19	233	228

4.1 VEHICLES WITH ON BOARD HYDROGEN STORAGE

The most rigorous analyses that DTI have performed is for vehicles that store hydrogen that has been generated at a fixed location and is stored on board the vehicle as a compressed gas. There is no added complexity or weight of an onboard reformer to consider. The DTI model compares the FCV to the same vehicle powered by an ICE and considers the extra weight of a FCV caused by the fuel cell system. Several driving cycles are compared and separate urban and highway results are presented. The typical results presented by DTI are summarized in Table 4-2. Small differences are found in different DTI papers and presentations with the more recent papers having lower values similar to those shown in this table.

Table 4-2 Relative Fuel Economy Ratios for Hydrogen Powered Fuel Cell Vehicles

Driving Cycle	Fuel Economy Ratio Relative to ICE
Federal Urban Driving Schedule	3.15
Federal Highway Driving Schedule	2.22
Combined (55 Urban/45 Highway)	2.62
1.25 Faster FUDS	2.6
1.25 Faster Highway	1.82
1.25 Faster Combined (55 Urban/45 Highway)	2.20

There will be no emissions of criteria pollutants from the hydrogen fuel cell vehicle.

4.2 VEHICLES WITH ON BOARD REFORMING

Fuel cell vehicles that produce their hydrogen onboard from fuels such as methanol, gasoline, or FT distillates have lower relative fuel economies compared to hydrogen vehicles. There are a number of reasons for this including;

- The inefficiency of the reforming process,
- Lower hydrogen utilization factors due to the need to vent carbon dioxide that is present in the reformate and losing some hydrogen in the vent gas before it can be converted to electricity,
- A lower hydrogen concentration of the fuel leading to a lower fuel cell efficiency and,
- Extra weight.

For a methanol fueled FCV, DTI projected a best case based on 84.5% (LHV) reformer efficiency, 90% hydrogen utilization. The combined relative fuel economy for this system on the faster driving cycle is 1.62. The basis for DTI's efficiency calculations is a 1994 study by A.D. Little that considered methanol reformers. Since that study was done Johnson Matthey (Kalhammer, Reinkingh) have published results for a methanol reformer that had an efficiency of 89.2% (LHV). Utilizing the higher reformer efficiency and considering the impact that has on heat recovery, the driving cycle efficiency increases to 1.72. Increasing the heat recovery efficiency from 75% to 80% would increase this ratio to 1.74. This is the ratio modeled here.

The exhaust emissions from the methanol reformer will obtain small amounts of unburned hydrocarbons, carbon monoxide and nitrogen oxides. There is very little quantitative data on these emissions particularly for a methanol reformer. Mark (1996) estimated NOx emissions of 0.001 g/mile, CO emissions of 0.003 g/mile and VOC emissions of 0.007 g/mile. This data is modeled. These emissions have a very small impact on GHG emissions so the uncertainty of the data is acceptable. It has also been suggested that NOx and CO emissions could be below detection limits. Real data is required before definitive conclusions can be reached.

A gasoline or FTD fuel cell vehicle is also expected to have lower efficiencies than hydrogen powered vehicles. DTI have calculated the relative fuel economy of a gasoline FCV to be 1.41 in their best case for the faster driving cycle. That is based on a reformer efficiency of 75%, 90% hydrogen utilization and 70% anode heat recovery. The case modeled here assumes 77% reformer efficiency, 90% hydrogen utilization and a 75% heat recovery. This is the best-demonstrated reformer performance and a similar improvement in heat recovery that methanol was assigned. This assumption may overestimate the potential heat recovery for gasoline given the exothermic nature of the gasoline reforming process and the endothermic methanol reforming process. The efficiency ratio improves to 1.45. The same ratio will be used for FTD reforming as for gasoline.

Epyx have reported preliminary emissions for their fuel processor operated on gasoline. The data is based on tests conducted on the reformer and extrapolated to a Federal Urban Driving cycle. They did not include the start up phase but also represent an early stage of development. The results were NOx 0.003 g/mile, CO emissions of 0.013 g/mile and hydrocarbon emissions of 0.017 g/mile. These are slightly higher than Mark reported for methanol, which is not unexpected. This data will be used in the model.

The greenhouse gas model used calculates the impact of vehicle and fuel weight separately from the impact of relative engine efficiency. In Table 4-3 the energy efficiency ratios of the three fuel cells before the weight adjustments are shown. These values are approximately 3 % higher than the DTI values and represent the efficiency of the fuel cell engine versus the fuel cell vehicle.

Table 4-3 Summary of Energy Efficiency Ratios for Hydrogen, Methanol, and Hydrocarbon Powered Fuel Cell Engines

Driving Cycle	Energy Efficiency Ratio	Energy Efficiency Ratio	Energy Efficiency Ratio
Fuel	Hydrogen	Methanol	Gasoline
1.25 Faster FUDS	2.63	1.94	1.72
1.25 Faster Highway	1.82	1.58	1.22
1.25 Faster Combined (55 Urban/45 Highway)	2.26	1.78	1.50

This vehicle information can be combined with the data developed in section 3 to calculate the full life cycle emissions for the various potential Fuel Cell Vehicles. That data will be presented in the next section.

5. RESULTS

The full cycle greenhouse gas emissions have been calculated for the base cases of the fuels and vehicle combinations described in the previous sections. The base for comparison is the internal combustion engine vehicle operating on low sulphur gasoline. The average vehicle on road fuel economy has improved from 9.6 L/100 km (24.6 m/USG) in 2000 to 9.0 L/100 km in 2010 (26.25 m/USG) The exhaust emissions are reduced from today's levels due in large part to low sulphur gasoline. The model is used to calculate the GHG emissions for both Canada and the United States. Qualitative comments are made for the potential situations in Japan and Europe.

5.1 BASE CASES - CANADA

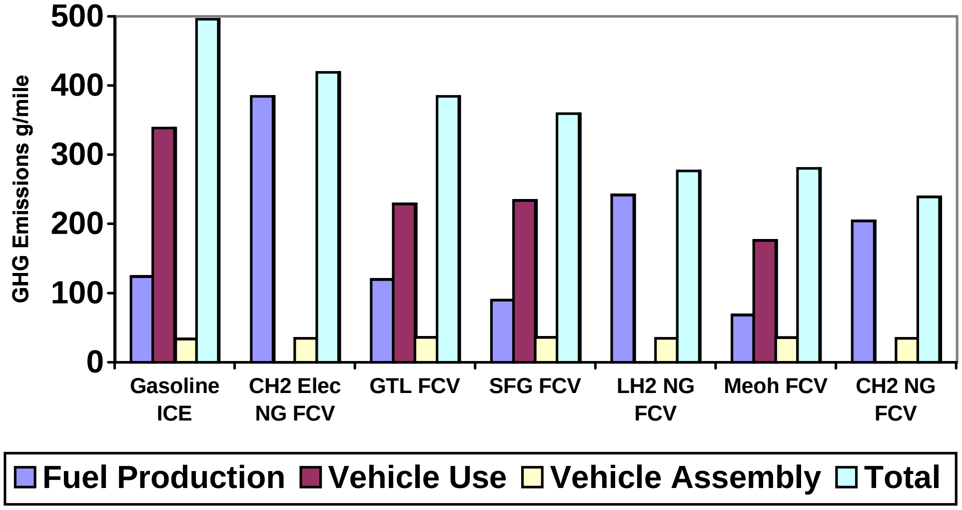
The results for Canada are shown in Table 5-1. All of the fuels are made in Canada from domestic oil and natural gas. The emissions are for the full cycle and include the energy and emissions embedded in vehicle manufacturing and assembly. These emissions are amortized over the life of the vehicle.

Table 5-1 Full Cycle Greenhouse Gas Emissions for Fuel Cell Vehicles - Canada

Engine	ICE	FC	FC	FC	FC	FC	FC
Fuel	Gasoline	CH_2	LH_2	CH_2	Methanol	Sulphur Free Gasoline	FTD
Source	Oil	NG (Small decentralize)	NG (Large centralized)	Electrolysis (natural gas to electricity)	NG	Oil	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	0.0	0.0	0.0	176.2	234.0	228.8
Fuel Dispensing	0.8	9.7	48.3	19.1	0.8	0.5	0.4
Fuel Distribution	5.8	0.6	1.7	0.6	15.6	4.0	8.9
Fuel Production	60.9	160.6	158.3	364.6	25.0	45.8	71.6
Feedstock Transport	1.0	7.1	7.1	0.0	1.1	0.7	1.6
Feedstock Production	42.5	11.9	11.8	0.0	15.0	29.4	22.3
Gas Leaks and Flares	12.8	14.4	14.5	0.0	10.8	8.9	16.1
Emissions Displaced by Co-products	0.0	0.0	0.0	0.0	0.0	0.0	-1.5
Sub Total	462.2	204.5	241.7	384.4	244.5	323.2	348.1
% Changes	**-**	**-55.8**	**-47.7**	**-16.8**	**-47.1**	**-30.1**	**-24.7**
Vehicle Assembly	5.3	5.4	5.4	5.4	5.8	5.9	5.9
Materials in Vehicles	28.4	29.2	29.2	29.2	29.9	30.4	30.4
Grand Total	495.9	239.1	276.3	419.0	280.2	359.5	384.4
% Change	**-**	**-51.8**	**-44.3**	**-15.5**	**-43.5**	**-27.5**	**-22.5**

The results are shown graphically in Figure 5-1.

Figure 5-1 Full Cycle Greenhouse Gas Emissions for Fuel Cell Vehicles – Canada



5.2 BASE CASES – UNITED STATES

The model is capable of calculating the results for the United States as well as for Canada. The results will be different due to several factors. These include;

- The US has electricity profile that is much more carbon intensive,
- The US refineries use more energy to make gasoline than Canadian refineries,
- The emissions in the oil and natural gas production sectors are different.

All of the other process variables for the various fuels are held constant and all of the transportation assumptions for raw materials supply and finished product distribution are unchanged from the Canadian case. Given the similarities in the size of the two countries these are reasonable assumptions. The fuel distribution emissions for methanol may be overestimated for the US case since some of the rail movements assumed for Canada would probably be replaced with barge shipments once volumes became larger. This mode of transport is more energy efficient than rail transport. Processes that are more electricity intensive will have higher greenhouse gas emissions in the United States than in Canada. The results are shown in Table 5-2.

The overall emissions are slightly higher in the United States than in Canada. Most of this difference is due to the higher carbon intensity of electricity generation. Emissions from natural gas production and distribution are almost the same in the two countries and the emissions from oil production, transport and refining in the two countries are within 2.5% of each other despite large differences in the sectors between the two countries.

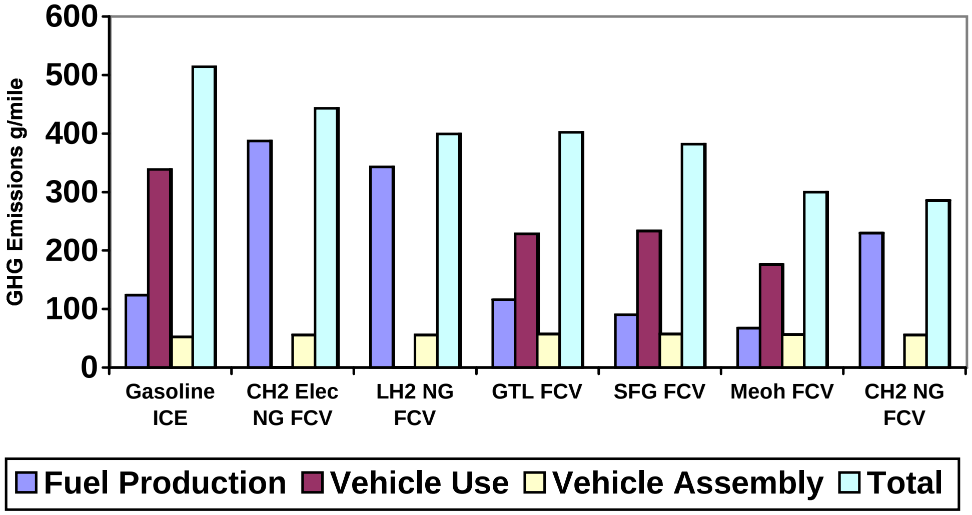
Table 5-2 Full Cycle Greenhouse Gas Emissions for Fuel Cell Vehicles- United States

Engine	ICE	FC	FC	FC	FC	FC	FC
Fuel	Gasoline	CH_2	LH_2	CH_2	Methanol	Sulphur Free Gasoline	FTD
Source	Oil	NG (Small decentralize)	NG (Large centralized)	Electrolysis (natural gas to electricity)	NG	Oil	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	0.0	0.0	0.0	176.2	234.0	228.8
Fuel Dispensing	2.0	29.6	147.0	19.2	2.2	1.4	1.2
Fuel Distribution	7.1	0.7	1.8	0.7	15.9	4.8	9.0
Fuel Production	72.1	163.2	158.3	367.3	25.0	54.8	71.6
Feedstock Transport	8.0	7.7	7.7	0.0	1.2	5.5	1.7
Feedstock Production	16.9	9.6	9.5	0.0	12.1	11.7	17.9
Gas Leaks and Flares	17.3	18.9	18.9	0.0	10.9	12.0	16.1
Emissions Displaced by Co-products	0.0	0.0	0.0	0.0	0.0	0.0	-2.1
Sub Total	461.9	229.8	343.2	387.3	243.5	324.2	344.4
% Changes	**-**	**-50.3**	**-25.7**	**-16.1**	**-47.3**	**-29.8**	**-25.4**
Vehicle Assembly	7.8	8.1	8.1	8.1	8.6	8.7	8.7
Materials in Vehicles	44.9	47.9	47.9	47.9	48.0	48.9	48.9
Grand Total	514.6	285.7	399.1	443.3	300.1	381.8	402.0
% Change	**-**	**-44.5**	**-22.5**	**-13.8**	**-41.7**	**-25.8**	**-21.9**

There are significant differences in the relative reductions of the options between Canada and the United States. These are caused primarily by the higher carbon intensity of electricity in the US. Any option that is more dependent on electricity will have higher emissions in the US than in Canada. The liquid hydrogen from natural gas is much less attractive than in Canada and there is now only a small difference between compressed hydrogen from natural gas and the onboard production of hydrogen from methanol.

The results are presented graphically in Figure 5-2. Note that there are no GHG emissions from the vehicle for the hydrogen FCV but the fuel production emissions are higher for these cases.

Figure 5-2 Full Cycle Greenhouse Gas Emissions for Fuel Cell Vehicles–United States



5.3 JAPAN AND EUROPE

The Japanese and European driving cycles are substantially different from North American cycles. They are slower and the higher efficiency of the FCV at low loads provides a greater fuel economy benefit than for the cycles modeled here. As shown in section 4 FCV are more efficient on the slower driving cycles. The GHG emissions per distance traveled for the urban part of the cycle will therefore be lower than North American values and for this part of the cycle the FCV will show a greater reduction in GHG emissions than they do for North America. The relative differences between fuel options for FCV are independent of the driving cycle and can be commented on.

The carbon intensity of electricity production in Japan and Europe is in between Canada and the United States. The fuel options Gasoline in an ICE, Methanol FCV, Sulphur Free Gasoline FCV and GTL FCV are relatively low consumers of electricity and produce similar results in Canada and the US. It is expected that the Japanese and European results would also be similar to those shown here.

The electricity consumption of the other options increases in this order; Compressed Hydrogen from Natural Gas, Liquid Hydrogen and Electrolytic Hydrogen. The full cycle emissions for Japan are expected to be approximately 62% of the way between those of Canada and the US. The emissions in Europe are expected to be 40% of the way between Canada and the US. A better understanding of the emissions in Europe and Japan will be developed at a later date.

5.4 ENERGY EFFICIENCY

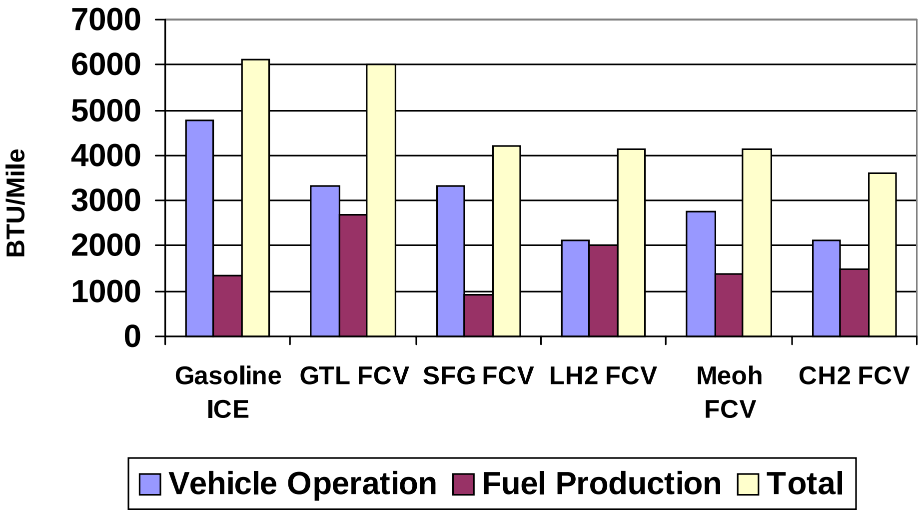
Different fuels have different amounts of GHG released for the same amount of energy. It is therefore informative to consider the total energy consumed per mile traveled as well as the greenhouse gas emissions for the various options. The data for Canada is shown in Table 5-3. The electricity pathways are not shown in the table because of the difficulty of assigning values to some of the generation paths such as hydro and nuclear.

Table 5-3 Energy Consumed per Mile Traveled

Engine	ICE	FC	FC	FC	FC	FC
Fuel	Gasoline	CH_2	LH_2	Methanol	Sulphur Free Gasoline	FTD
Source	Oil	NG	NG	NG	Oil	NG
Units	BTU/Mile	BTU/Mile	BTU/Mile	BTU/Mile	BTU/Mile	BTU/Mile
Vehicle Operation	4,782	2,124	2,124	2,761	3,307	3,307
Fuel Dispensing	8	138	686	10	6	6
Fuel Distribution	43	207	219	136	30	78
Fuel Production	706	910	870	1,032	489	2,326
Feedstock Transport	11	95	94	14	7	21
Feedstock Production	577	146	145	184	399	272
Total	6,128	3,621	4,138	4,138	4,215	6,010

The energy consumption results are presented graphically in Figure 5-3.

Figure 5-3 Energy Consumption per Mile



6. SENSITIVITY ANALYSES

The cases and results presented in the previous sections represent what the best technology would produce in a North American location and with moderate market penetration of FCV. It is likely that some of this production technology will not be built in North America but in more remote locations where natural gas costs are lower and the emissions from natural gas production may be lower. There is also the possibility that other technologies will be used because of cost or they may be more appropriately sized, especially during the early years of market development. Some of these possibilities are investigated here.

6.1 NATURAL GAS EMISSIONS

The emissions from the production and transmission of natural gas to the fuel production facility comprise 9 to 14% of the full cycle GHG emissions for the options studied here. Large facilities that can be built close to the gas production areas such as the methanol and GTL plants modeled here can reduce the emissions arising from transportation and distribution. Another opportunity for reducing the emissions is to reduce losses of methane as the industry is currently undertaking. To determine the magnitude of this change the rate of improvement in this area assumed in the model is quadrupled to determine the impact on full cycle emissions in the year 2010. The improvement rates become 4% distribution and recovery systems and 2% for transmission, storage and processing operations. No changes to the other emission rates for gas processing are made.

The changes in the full cycle GHG emissions for the methanol, compressed hydrogen from SMR and the GTL process are shown in Table 6-1.

Table 6-1 Emission Impact of Reducing Gas System Methane Losses

	Base Case	Low Methane Losses	% Change
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	
Methanol			
Gas Production	26.9	23.9	-11.2
Full Cycle	280.2	276.9	-1.2
Compressed Hydrogen			
Gas Production	33.4	29.4	-12.0
Full Cycle	239.1	234.6	-1.9
GTL			
Gas Production	40.0	35.5	-11.2
Full Cycle	384.4	379.8	-1.2

The reduction in methane losses from the natural gas system can make a significant impact on the GHG emissions from that stage of the life cycle but the reduction is relative small when considered over the full life cycle of the full and vehicle option and the impact is similar on all of the natural as based pathways.

6.2 HYDROGEN FROM NATURAL GAS

There are two possible alternative cases for natural gas to hydrogen. The first is the use of Partial Oxidation Reformers instead of Steam Methane Reformers and the second is the liquefaction of natural gas in a remote location, shipping it to market and then vapourizing the gas for use in a domestic natural gas system. These two cases are studied below.

6.2.1 Partial Oxidation Reformers

The production of hydrogen from Steam Methane Reforming (SMR) of natural gas is the most efficient process but it is better suited to larger systems. Partial Oxidation (POX) reformers can also be used to produce hydrogen from natural gas. These systems are generally smaller, with lower capacity than SMR, have a lower capital cost but are not as efficient. They may be easier to start up and shutdown and thus better suited to the load factor of a service station. The smaller size may be better suited to a service station type installation than a SMR.

Phoenix Gas Systems manufacture a POX reactor combined with a Pressure Swing Absorption unit. The largest size is capable of producing 10 kg/hr of hydrogen. This would support about 350 vehicles at a station. This is equivalent to the number of vehicles that might buy premium gasoline at a typical Canadian service station.

The utility requirements for this unit are 2180 SCF of natural gas per million BTU of hydrogen produced and 54 kWh of electricity per million BTU of hydrogen (43.3% efficiency). The other parameters for compressed hydrogen systems have been held constant. In Table 6-2 the GHG emissions for a POX system are compared with those of a SMR system and the gasoline ICE.

Table 6-2 GHG Emissions from a POX Reformer for Hydrogen Production Canada

Engine	ICE	FC	FC
Fuel	Gasoline	CH_2	CH_2
Source	Oil	SMR NG (Small decentralize)	POX NG (Small decentralized)
Source	Oil	NG	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	0.0	0.0
Fuel Dispensing	0.8	9.7	10.0
Fuel Distribution	5.8	0.6	0.6
Fuel Production	60.9	160.6	272.8
Feedstock Transport	1.0	7.1	11.0
Feedstock Production	42.5	11.9	18.3
Gas Leaks and Flares	12.8	14.4	22.2
Sub Total	462.2	204.5	335.0
% Changes	**-**	**-55.8**	**-27.5**
Vehicle Assembly	5.3	5.4	5.8
Materials in Vehicles	28.4	29.2	31.3
Grand Total	495.9	239.1	372.1
% Change	**-**	**-51.8**	**-25.0**

The greenhouse gas emissions benefit from a compressed hydrogen fuel cell vehicle is reduced by half with the use of a POX reactor system for hydrogen production. This is a significant reduction that makes this lower cost hydrogen production system less attractive from a GHG perspective.

The same case is modeled for the United States. The relatively high electricity consumption coupled with the carbon intensity of the US electricity produces a substantially different result with a much lower GHG reduction. The results are shown in Table 6-3.

Table 6-3 GHG Emissions from a POX Reformer for Hydrogen Production US

Engine	ICE	FC	FC
Fuel	Gasoline	CH_2	CH_2
Source	Oil	SMR NG (Small decentralize)	POX NG (Small decentralized)
Source	Oil	NG	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	0.0	0.0
Fuel Dispensing	2.0	29.6	29.6
Fuel Distribution	7.1	0.7	0.7
Fuel Production	72.1	163.2	329.0
Feedstock Transport	8.0	7.7	11.9
Feedstock Production	16.9	9.6	14.8
Gas Leaks and Flares	17.3	18.9	29.1
Sub Total	461.9	229.8	415.1
% Changes	**-**	**-50.3**	**-10.1**
Vehicle Assembly	7.8	8.1	8.1
Materials in Vehicles	44.9	47.9	47.9
Grand Total	514.6	285.7	471.1
% Change	**-**	**-44.5**	**-8.5**

6.2.2 Liquid Natural Gas

Not all countries have indigenous supplies of natural gas sufficient to supply all of their needs. Some of these countries rely on the importation of liquefied natural Gas (LNG). LNG is a cryogenic liquid with a much higher energy density than compressed natural gas. There is a sizeable world trade in LNG. The United States and Japan are two countries that are importers of LNG. The natural gas is assumed to be liquefied in a region with remote gas using natural driven compressors to drive the process. It is then move by LNG tanker the same 5500 km distance that has been assumed for the other liquid remote gas cases. The natural gas is then vapourized and shipped a further 300 miles by pipeline to the service station for conversion to hydrogen in a SMR. This essentially assumes that LNG would be used in the coastal regions and not throughout the whole country. LNG is being used to augment and not to replace existing supplies. The full cycle emissions for the United States for this case are compared to gasoline in an ICE, domestic natural gas and domestic methanol production in the following table. The United States is a more appropriate comparison than Canada since it is not likely that Canada will be an importer of LNG in the foreseeable future.

Table 6-4 GHG Emissions from Remote LNG for Hydrogen Production

Engine	ICE	FC	FC
Fuel	Gasoline	CH_2	CH_2
Source	Oil	SMR NG (Small decentralize)	SMR NG (Small decentralize)
Source	Oil	NG	LNG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	0.0	0.0
Fuel Dispensing	2.0	29.6	29.6
Fuel Distribution	7.1	0.7	0.7
Fuel Production	72.1	163.2	163.2
Feedstock Transport	8.0	7.7	7.3
Feedstock Production	16.9	9.6	45.8
Gas Leaks and Flares	17.3	18.9	26.7
Sub Total	462.2	229.8	273.2
% Changes	**-**	**-50.3**	**-40.8**
Vehicle Assembly	7.8	8.1	8.1
Materials in Vehicles	44.9	47.9	47.9
Grand Total	514.6	285.7	329.1
% Change	**-**	**-44.5**	**-36.1**

There is a significant increase in GHG emissions for the LNG case. In the next section the case of a remote methanol plant will be considered and a further comparison will be made between remote gas via LNG to remote gas via methanol.

6.3 METHANOL

Two sensitivity cases for methanol are considered, a remote methanol plant that would take advantage of low cost remote natural gas and the impact of natural gas composition is investigated.

6.3.1 Remote Methanol Plants

New methanol plants are being built today in areas that have low cost natural gas. Most of these areas are remote and a long distance from markets, which accounts for the low gas cost. The gas fields supplying these plants are relatively new and the plants will be located very close to the field. The gas supply to the methanol plant will assume the low methane emission rate modeled in the sensitivity case above, a shorter relative distance between the plant and the field of 5% rather than the 12%. The emissions from gas production and processing will be the same as modeled for Canada due to the lack of specific data for these remote gas fields. The specific case of flared gas being utilized for methanol production has not been considered. While the flared gas resource is substantial it is ultimately limited and could only power a small fraction of the world's vehicles.

There will be a significant change in the distribution of the methanol to the market. It will be assumed that the product will move 5500 miles by ship, and average of 200 miles by rail and the same 75 miles by truck. The rail distances are much less than the base case but are reasonable given that a large fraction of the Canadian population is located close to water. The results of this case are presented in Table 6-5. There is very little difference in the emissions due to the remote location. Ocean shipment is a more energy efficient mode of transportation than rail. The energy use for the ocean shipping is modeled based on data from Methanex's newest ocean vessel, the 100,000 tonne Millennium Explorer. The 5500 mile distance is considered to be more than sufficient to move methanol to Canada and the US from a mix of remote locations including South America, the Caribbean, the North Sea and the Middle East.

Table 6-5 Impact of a Remote Methanol Plant on GHG Emissions

Engine	ICE	FC	FC
Fuel	Gasoline	Methanol	Methanol
Source	Oil	Canada	Remote Location Low Methane Losses
Source	Oil	NG	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	176.2	176.2
Fuel Dispensing	0.8	0.8	0.8
Fuel Distribution	5.8	15.6	15.8
Fuel Production	60.9	25.0	25.0
Feedstock Transport	1.0	1.1	0.4
Feedstock Production	42.5	15.0	14.8
Gas Leaks and Flares	12.8	10.8	7.8
Sub Total	462.2	244.5	240.9
% Changes	**-**	**-47.1**	**-47.8**
Vehicle Assembly	5.3	5.8	5.8
Materials in Vehicles	28.4	29.9	29.9
Grand Total	495.9	280.2	276.6
% Change	**-**	**-43.5**	**-44.2**

The transportation emissions are remarkably similar in the two cases. The primary differences for the case arise from the low methane loss assumption for a methanol plant located very close to the source of gas.

This remote gas to methanol case for the United States is now compared to the LNG option in the following table. It can be seen that for this scenario GHG emissions are lower for methanol than for compressed hydrogen. For a country like Japan where essentially all of the natural gas is imported as LNG it is likely that methanol FCV will have lower full cycle emissions than hydrogen FCVs. The lower carbon intensity of Japanese electrical production compared to the US will not be sufficient to overcome the methanol advantage shown below.

Table 6-6 Comparison of Remote Gas Options for the United States

Engine	ICE	FC	FC
Fuel	Gasoline	Methanol	CH_2
Source	Oil	Remote Location Low Methane Losses	SMR NG (Small decentralize)
Source	Oil	NG	LNG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	176.2	0.0
Fuel Dispensing	2.0	2.2	29.6
Fuel Distribution	7.1	15.8	0.7
Fuel Production	72.1	25.0	163.2
Feedstock Transport	8.0	0.4	7.3
Feedstock Production	16.9	14.8	45.8
Gas Leaks and Flares	17.3	7.8	26.7
Sub Total	462.2	242.2	273.2
% Changes	**-**	**-47.6**	**-40.8**
Vehicle Assembly	7.8	8.6	8.1
Materials in Vehicles	44.9	48.0	47.9
Grand Total	514.6	298.8	329.1
% Change	**-**	**-41.9**	**-36.1**

6.3.2 Natural Gas Composition

The composition of natural gas can have an impact on GHG emissions from the fuel processor since the carbon to hydrogen ratio can change relative to the energy content of the fuel and the gas may contain some inert CO_2, which goes through the process unchanged. It theory this will impact all natural gas based systems but in practice it is most likely to impact remote gas processing where the higher hydrocarbons are not removed for further upgrading. To show the magnitude of the change, the upstream emissions that would result from a methanol plant processing raw Norwegian gas are compared to those calculated here for Canadian gas. All plant energy efficiencies are held constant so that the only variable is the gas composition. The results are compared in the following table.

Table 6-7 Impact of Gas Composition on GHG Emissions for Methanol Plant

	Emissions	Emissions
Gas Source	Norway	Canada
Gas Consumption	31.2 GJ/tonne	31.2 GJ/tonne
Units	Gms CO_2 / million BTU dispensed	Gms CO_2 / million BTU dispensed
Fuel Dispensing	279	279
Fuel Distribution and Storage	5,704	5,655
Fuel Production	14,058	9,049
Feedstock Transmission	405	393
Feedstock Recovery	5,745	5,429
Gas Leaks and Flares	2,677	2,995
CO_2 from Natural Gas	809	925
Total	29,645	24,725

The emissions from the plant are 55% higher with small changes in some of the other categories due to the different gas composition and the different density of the gas. Gas composition data from other remote gas locations was obtained to gain an understanding of the likely gas composition from remote locations. That data is shown in Table 6-7 and compared to the Canadian gas composition used in this modeling.

Table 6-8 Gas Composition For Remote Locations

	Canada	Chile	Australia	Trinidad	Norway
Components	Vol %	Vol %	Vol %	Vol %	Vol %
Methane	94.4	93.46	91.6	95.39	80.9
Ethane	2.7	4.95	5	3.91	9.4
Propane	0.4	0.18	0.4	0.03	4.4
Butane	0.1	0.03	0.1		3.1
Pentane	0.06	0.0	0.0		0.0
Pentane plus	0.04	0.0	0.0		0.0
Carbon dioxide	0.5	0.2	0.8	0.59	1.8
Nitrogen	1.8	1.18	2.1	0.08	0.4
Total	100	100	100	99.97	100

The Norwegian gas appears to be an anomaly with the other gas sources being much closer to the data used here. With very large gas developments there is usually a financial incentive to remove the heavier hydrocarbons for further value added processing.

6.4 LIQUID HYDROGEN

A high penetration rate of hydrogen powered FCV may make very large-scale liquid hydrogen plants a possibility. It will be assumed that these plants have a natural gas utilization of 1250 SCF per million BTU of hydrogen, there is no extra electricity required for the hydrogen production stage. No changes have been made to the liquefaction energy requirements and the transportation distance is reduced to 200 miles from 300 miles reflecting the higher market penetration.

The results for this scenario are shown in Table 6-9 and compared to the gasoline ICE and the base case for liquid hydrogen. Full cycle greenhouse gas emissions are reduced by 10.6% compared to the base case for this high efficiency SMR system. These results are for Canada where the electricity has relatively low carbon intensity. The difficulty with this scenario is the size of the market required to support a very large facility and how quickly the FCV demand can be built to match the hydrogen supply.

Table 6-9 GHG Emissions for High Efficiency Liquid Hydrogen System

Engine	ICE	FC	FC
Fuel	Gasoline	Liquid Hydrogen	Liquid Hydrogen
Case		Base Case	High Efficiency
Source	Oil	NG	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	0	0
Fuel Dispensing	0.8	48.3	48.3
Fuel Distribution	5.8	1.7	1.2
Fuel Production	60.9	158.3	143.6
Feedstock Transport	1.0	7.1	6.4
Feedstock Production	42.5	11.8	10.7
Gas Leaks and Flares	12.8	14.5	13.1
Sub Total	462.2	241.7	223.4
% Changes	**-**	**-47.7**	**-51.7**
Vehicle Assembly	5.3	5.4	5.4
Materials in Vehicles	28.4	29.2	29.2
Grand Total	495.9	276.3	258.0
% Change	**-**	**-44.3**	**-48.0**

6.5 GTL PLANTS

Gas to Liquids plants are at an early stage of technological development. As such there is still a great deal of uncertainty with respect to the energy efficiency of these plants. The base case modeled use a gas utilization factor that is widely quoted in the literature. As noted early Gradassi has performed economic modeling on plants that use 20% less gas as well as plants that use 15% more gas. GTL plants are also most likely to be built at remote locations where low cost natural gas can be obtained.

This sensitivity case is performed with all of the remote gas characteristics the same as the remote methanol case and a gas conversion factor of 202 SCF/USG of FTD. The results and comparison with the base case and a gasoline powered ICE is shown in Table 6-10.

Table 6-10 GHG Emissions for a High Efficiency GTL Plant and FCV

Engine	ICE	FC	FC
Fuel	Gasoline	FTD	FTD
Case		Base Case	High Efficiency
Source	Oil	NG	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	228.8	228.8
Fuel Dispensing	0.8	0.4	0.4
Fuel Distribution	5.8	8.9	7.9
Fuel Production	60.9	71.6	26.4
Feedstock Transport	1.0	1.6	0.6
Feedstock Production	42.5	22.3	18.9
Gas Leaks and Flares	12.8	16.1	13.3
Co-products		-1.5	-1.5
Sub Total	462.2	348.1	294.8
% Changes	**-**	**-24.7**	**-36.2**
Vehicle Assembly	5.3	5.9	5.9
Materials in Vehicles	28.4	30.4	30.4
Grand Total	495.9	384.4	331.1
% Change	**-**	**-22.5**	**-33.2**

7. COMPARISON TO OTHER STUDIES

It is useful to compare the results calculated here with those of other published studies. While a number of studies were identified in section that dealt with the full life cycle emissions of transportation fuels very few of them addressed fuel cell vehicles due to the newness of the technology. The Delucchi model as first delivered to NRCan was capable of looking at the fuel part of the fuels considered here but did not include a fuel cell vehicle for the vehicle part of a full cycle. Delucchi (1992) analyzed hydrogen fuel cell vehicles primarily from a life cycle cost perspective. For the year 2000 he projected a 43% reduction in GHG emissions for a natural gas to hydrogen FCV. That value is remarkably similar to the 44.5% reduction for the United States that was calculated here. The other fuel cycles considered by Delucchi were biomass or solar powered and can't be compared to the cycles considered here.

Two recent studies and an update on full cycle greenhouse gas emissions have been published by Wang (1999, 1999b, 2000). Both of these studies use the Greet model, are based primarily on US data and contain many of the same vehicle and fuel combinations that are of interest here. The assumptions for each of the fuel cycles may be different from the judgements made in this study nevertheless the comparison can be informative. In Wang's most recent work (1999b, 2000) he reports on two cases, an incremental scenario and a leap forward scenario. All three of Wang's cases are shown in Table 7-1 and are compared to the results found here.

Table 7-1 Comparison to Other Studies

	Wang August 1999 Greet 1.5	Wang January 2000. Greet 1.5a Natural Gas Pathways.	Wang January 2000. Greet 1.5a Natural Gas Pathways.	This Report United States	This Report Canada
Scenario		Incremental	Leap Forward	Base Case	Base Case
	% Reduction from Gasoline ICE	% Reduction from Gasoline ICE	% Reduction from Gasoline ICE	% Reduction from Gasoline ICE	% Reduction from Gasoline ICE
CH2, decentralized	61.2	54.8	60.5	44.5	51.8
LH2, centralized	61.0	45.0	55.1	22.5	44.3
Methanol	60.5	51.3	60.5	41.7	43.5
SF Gasoline	50.6	43.7	56.1	25.8	27.5

Wang predicts greater reductions in GHG than does this study. This is in large part to do much higher relative fuel economies assumed by Wang. The hydrogen FCV has a relative fuel economy of 3.0 in Greet 1.5, 2.8 for the incremental scenario and 3.2 for the leap forward case described in GREET 1.5a. These are all higher than the 2.2 used for this study. Wang's relative fuel economy values for methanol FCV vary from 2.1 to 2.6 and for gasoline from 1.75 to 2.25. Interestingly, the ratio of methanol to hydrogen relative fuel economy used by Wang (0.79) is the same as calculated for this study.

If Wang's results are adjusted for the lower vehicle efficiency used in this study, then the revised results for methanol and compressed hydrogen (a 42.2% reduction in GHG) are very similar to those calculated here for the United States. There are still differences for gasoline (an adjusted value for Wang would be a 36% reduction) and for liquid hydrogen (adjusted to

42.6% reduction). Wang has assumed that large hydrogen liquefaction plants are able to generate a portion of their electrical requirements from surplus steam that they generate and no such assumption is made here.

Levelton (1999) studied and reported on a wide variety of propulsion systems and fuels for the National Climate Change Process Transportation Table in Canada. Hydrogen and methanol fueled FCV were included in the study. A comparison of those results and those reported here is shown in Table 7-2.

Table 7-2 Comparison of Levelton Results with This Study

	Levelton	This Study
	% reduction from gasoline ICE	% reduction from gasoline ICE
Methanol FCV	39	43.5
Hydrogen from Natural Gas	53	51.8
Electrolytic Hydrogen	49	53.6

The Levelton hydrogen natural gas reformer efficiency was very high and is probably not achievable in the 2010 time period and the relative vehicle efficiencies were slightly lower than those used here. These two inputs account for most of the differences.

The Pembina Institute for Appropriate Development (2000) released a report on the life cycle greenhouse gas emissions for selected fuel cell vehicle systems. This study used a life cycle assessment approach and considered all of the stages considered here except the vehicle materials and vehicle assembly and transport. The authors gathered data from a wide variety of sources, including previous work by $(S\&T)^2$. The results are shown in Table 7-3 and compared to the Canadian results reported here. The data for this report in Table 7-3 does not include the vehicle materials and assembly to be consistent with the Pembina approach.

Table 7-3 Comparison of Pembina Institute Results

	Pembina	This Report
	% reduction in GHG emissions	% reduction in GHG emissions
Compressed Hydrogen	67.7	55.8
On Board Methanol	34.6	47.1
On Board Gasoline	22.2	30.1
Electrolytic Hydrogen (electricity from natural gas)	4.4	16.8

The results are quite different although they are in the same relative order. The differences appear to be in the relative vehicle efficiencies chosen by Pembina. It is not clear from the Pembina report if the data all came from the same source or if the hydrogen data came from a different source to the gasoline and methanol data. The driving cycle used for comparison appears to be the combined urban and highway EPA cycle rather than the faster cycle used here. The following table compares the vehicle efficiency factors used in the Pembina study to those used here.

Table 7-4 Comparison of Pembina Vehicle Energy Efficiency Factors

	Pembina	Pembina	This Study
	Fuel Economy, USMPG	Vehicle Energy Efficiency ratio to gasoline ICE	Vehicle Energy Efficiency ratio to gasoline ICE
Gasoline ICE	32		
Hydrogen FCV	84.2	2.63	2.2
Methanol FCV	56.2	1.76	1.74
Gasoline FCV	38.5	1.20	1.45

The much larger range in vehicle efficiency ratios used by Pembina accounts for the larger range in GHG emission reductions reported by them. If the hydrogen FCV modeled by Pembina had used the 2.2 vehicle efficiency factor the reduction in GHG emissions would be 56.6% which is very close to that reported here. For the methanol FCV the differences between this study and the Pembina report are in the production of natural gas and the production of methanol. Pembina used an older source of data for natural gas production emissions than was used for this study. Their assumption for emissions from a methanol plant were based on conventional steam reforming rather than the more energy efficient combined reforming technology used for this study. The new methanol plants being built around the world today are using technologies more advanced than conventional steam reforming.

The studies report differing results for GHG emissions reduction potential for FCV and the various possible fuels for those vehicles. The differences between studies can usually be explained by the different assumptions used in the development of the data. Since FCV are still at a very early stage of development and good test data is not readily available it is understandable that different authors might make different assumptions about the future technology. As shown above the different results can usually be explained.

All of the studies have indicated a reduction in GHG emissions for methanol powered FCV. The degree of reduction is dependent on the assumptions made.

8. CONCLUSIONS

Fuel cell vehicles offer the potential to significantly reduce the greenhouse gas emissions from the transportation sector. The reductions are due to a higher efficiency for the fuel cell compared to the internal combustion engine and a different load profile that results in much higher efficiencies particularly at low load. The magnitude of the reduction in GHG is dependent on the fuel used to power the FCV, where and how that fuel is produced.

In Canada the greatest reduction in GHG would be from the use of compressed hydrogen manufactured by SMR of natural gas. There are concerns regarding the practicality of this option for decentralized service stations. If POX units are used instead of SMR plants the GHG benefit is reduced by one half. The next greatest reductions come from centralized liquid hydrogen plants and from methanol reformed to hydrogen onboard the vehicle. The production of hydrogen onboard the vehicles from sulphur free gasoline or Fischer Tropsch distillate produce smaller reductions in greenhouse gases. Hydrogen produced by electrolysis from electricity produced by natural gas yields the lowest GHG reductions.

In the United States the results are somewhat different due to the higher carbon intensity of electricity generation in that country. The decentralized compressed hydrogen from SMR still has the greatest reduction but the centralized liquid hydrogen option is not as attractive as methanol reformed on board the vehicle. These are followed by the onboard reforming of gasoline and FTD, liquid hydrogen from natural gas, and electrolytic hydrogen from high efficiency gas turbines and hydrogen produced by POX systems. The percent change in GHG emissions from the various fuels for both countries is shown in Table 8-1.

Table 8-1 Reductions in GHG Emissions for Fuel Cell Vehicles in Canada and the US

Fuel	Source	% Reduction in Canada	Fuel	Source	% Reduction in the US
CH_2	Natural Gas SMR	51.8	CH_2	Natural Gas SMR	44.5
LH_2	Natural Gas SMR	44.3	Methanol	Natural Gas	41.7
Methanol	Natural Gas	43.5	Sulphur Free Gasoline	Crude Oil	25.8
Sulphur Free Gasoline	Crude Oil	27.5	LH_2	Natural Gas SMR	22.5
CH_2	Natural Gas POX	25.0	FT Distillate	Natural Gas	21.9
FT Distillate	Natural Gas	22.5	CH_2	Natural Gas to Electricity	13.8
CH_2	Natural Gas to Electricity	15.5	CH_2	Natural Gas POX	8.5

Not all countries have local supplies of natural gas and some, such as Japan, rely on the importation of Liquefied Natural Gas for their domestic gas requirements. For these areas methanol made from the same remote gas as the LNG would be produced from will provide a greater reduction in GHG's than will the natural gas to hydrogen option. Using the US electricity mix for the distribution phases (but not the fuel production phases) and using 300 miles as the inland distribution distance for both the methanol and LNG option the methanol option reduced GHG gases by 41.9% and the LNG option reduced emissions by 36.1%. The results are shown in the following table.

Table 8-2 Comparison of Remote Gas Options for the United States

Engine	ICE	FC	FC
Fuel	Gasoline	Methanol	CH_2
Source	Oil	Remote Location Low Methane Losses	SMR NG (Small decentralize) Low Methane Losses
Source	Oil	NG	LNG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	176.2	0.0
Fuel Dispensing	2.0	2.2	29.6
Fuel Distribution	7.1	15.8	0.7
Fuel Production	72.1	25.0	163.2
Feedstock Transport	8.0	0.4	7.3
Feedstock Production	16.9	14.8	45.8
Gas Leaks and Flares	17.3	7.8	26.7
Sub Total	462.2	242.2	273.2
% Changes	**-**	**-47.6**	**-40.8**
Vehicle Assembly	7.8	8.6	8.1
Materials in Vehicles	44.9	48.0	47.9
Grand Total	514.6	296.7	323.5
% Change	**-**	**-41.9**	**-36.1**

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Appendix A Delucchi Model.

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. This segment is only applicable to biomass based cycles.
- 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 for biomass based fuels arising from use of a renewable carbon source that obtains carbon from the air. This is consistent with IPCC guidelines.
- 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. This is also a factor for processes that also produce electricity and/or steam as part of the alternative fuel production process.
- 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.

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.