HYDROGEN PATHWAYS
GREENHOUSE GAS EMISSIONS AND ENERGY USE

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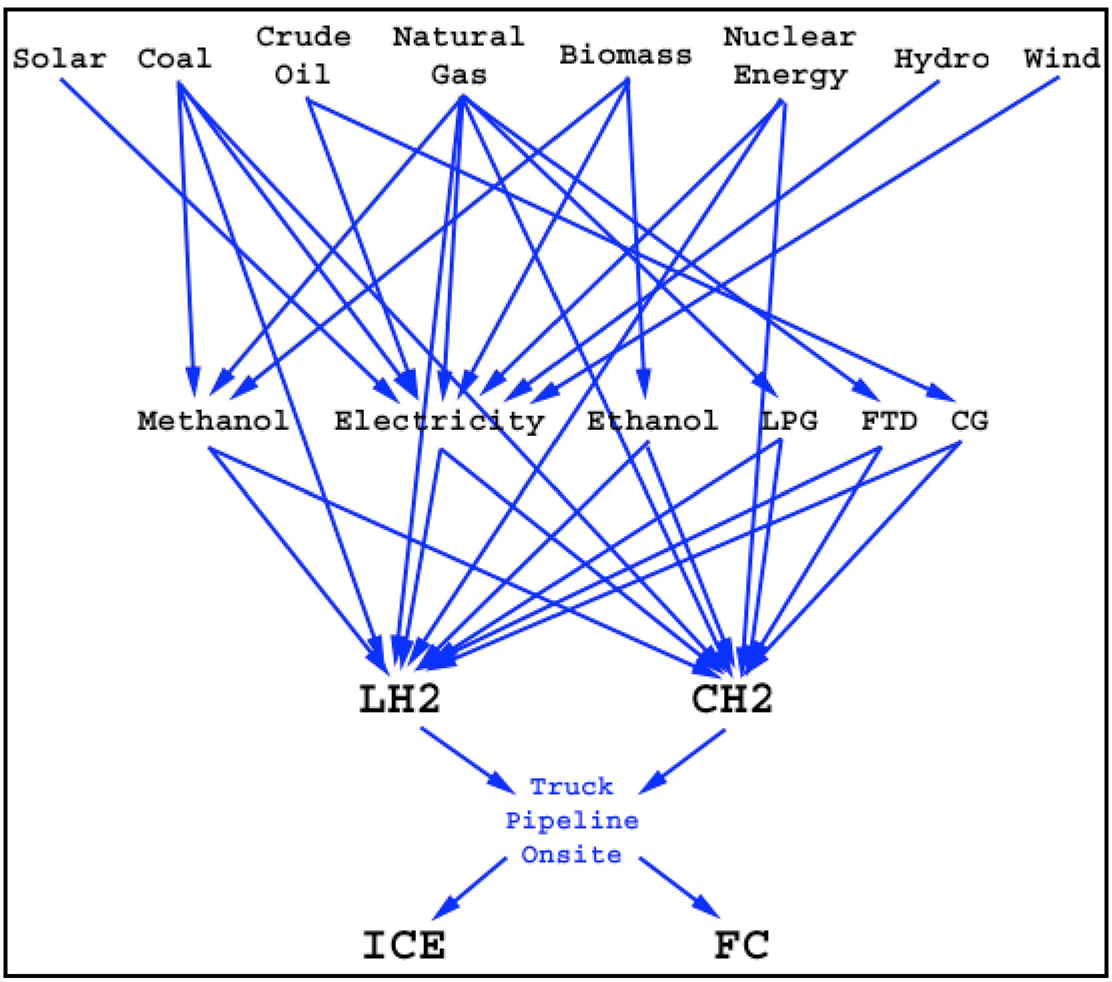
EXECUTIVE SUMMARY

Under the Kyoto Protocol, Canada committed to reduce GHG emissions by 6% from 1990 levels by the period 2008 to 2012. The transportation sector represents the single largest source of Canada's GHG emissions, accounting for 27 per cent of the total. Transportation emissions arise from all sectors of the commercial economy and are inherent to the movement of people and goods for social and recreational activities. Hence, measures to reduce emissions from the transportation sector must be considered very carefully and respect the ramifications of such measures on the economy and peoples day-to-day activities. Emissions from transportation are growing faster than the average for all emissions and are forecast to exceed 1990 levels by 26 per cent in 2010 and 42 per cent by 2020.

There is currently a great deal of discussion in Industry, Government and Academic forums regarding the development of a "Hydrogen Economy". This future economy is seen by many as a means to reduce greenhouse gas emissions, to provide better urban air quality, and increased energy security. The large number of pathways between the raw energy resource and hydrogen provides the increased energy security. In the following figure this is illustrated.

Figure ES-1 Hydrogen Pathways



As this vision of a "Hydrogen Economy" evolves, more and more pathways are being identified. While some pathways will provide greenhouse gas benefits it is possible that others may not.

This project utilized Natural Resources Canada's GHGenius ($(S\&T)^2$, 2003) model for the quantification of the lifecycle energy consumption and emission profiles of many technically feasible hydrogen pathways. The hydrogen pathways that are studied include the following components:

> Feedstocks. The following feedstocks can be converted to hydrogen: coal, crude oil, natural gas, biomass, nuclear energy, and hydropower (can also be used as a proxy for wind and solar).
>
> Intermediate Products. In addition to the direct production of hydrogen, some of the feedstocks mentioned above can produce various intermediate energy carriers that can be used for the eventual production of hydrogen; these include methanol, electricity, ethanol, LPG, FT Distillate, and gasoline.
>
> Distribution. Hydrogen can be produced on site or it can be produced at a central facility. The distribution from a central facility can be as a liquid or a compressed gas. The compressed gas can be distributed by pipeline or by truck. Liquid hydrogen can be distributed by truck or rail. Some of the pathways will only be feasible with large central facilities that require hydrogen distribution while others could be small decentralized systems or large central systems. The impacts of the distribution system on the results are discussed and the most likely option for each pathway can be modeled.
>
> Utilization. The hydrogen could be used in an internal combustion engine or in a fuel cell. The data in GHGenius for the hydrogen ICE has been reviewed with a literature search to ensure that it is consistent with the latest developments in this area.

Fifty pathways for transportation fuels have been evaluated for their lifecycle greenhouse gas emissions. Forty-five of those involve hydrogen. Thirty-six pathways have been investigated for their energy use and thirty-one of those involve hydrogen.

All new innovations including the "Hydrogen Economy" have to provide multiple benefits to individuals and society in order to be adopted. In the case of hydrogen, certain pathways are unlikely to be adopted if they provide energy security benefits without reductions in greenhouse gas emissions and a positive benefit to cost ratio for the adopters. While it is beyond the scope of this work to evaluate the costs of the different hydrogen pathways it has been possible to compare the greenhouse gas emissions and energy balances of many of the hydrogen pathways on a common basis.

GHG emissions for the hydrogen pathways range from 1.3% to 395% of the emissions of the gasoline baseline vehicle. With such a wide range in the GHG emission and energy use results it is clear that an unmanaged "Hydrogen Economy" is not a panacea for solving the GHG emissions problem or for resolving the energy security issues for energy importing nations. There are hydrogen pathways that can produce very significant GHG emission reductions and energy savings but there are also pathways that would result in increased GHG emissions and increased energy use. One of the challenges of managing a transition to a hydrogen economy will therefore be ensuring that society does receive the maximum possible benefits.

Hydrogen pathways are more likely to provide benefits if fuel cells are used to convert the hydrogen to useful work rather than using an internal combustion engine. The benefits arise from the higher efficiency of the fuel cell compared to the hydrogen internal combustion engine. It is forecast that the fuel cell will be more than twice as efficient as the hydrogen internal combustion engine in transportation applications. Even if there are breakthroughs with the internal combustion engine and no further development of the fuel cell the fuel cell will still be 50% more efficient than the ICE.

There are 14 pathways with GHG emissions of less than 20% of the baseline gasoline vehicle. These pathways have very low emissions on both FC and ICE vehicles but most of them are for technologies that have not yet been demonstrated on a commercial scale. Of the top 14 pathways only hydrogen from electrolysis from nuclear power or hydroelectricity could be considered commercial hydrogen production pathways. While there is some potential to increase hydroelectricity in Canada there is not enough potential to supply all transportation needs. Nuclear power could be expanded if the public acceptance issues could be overcome.

The GHG emissions from electrolysis vary significantly depending on the energy source used to produce the hydrogen. Electricity from a coal-fired power plant leads to increases in GHG emissions when used in either fuel cells or internal combustion engines. When the electricity is produced in a combined cycle natural gas fired power plant there is a small reduction in GHG emissions when the hydrogen is used in fuel cell vehicles but an increase when the hydrogen is used in internal combustion engines. In most regions of Canada one of these two electricity generating systems is used as the incremental source of electricity.

The GHG emissions from electrolytic hydrogen are very low when the electricity is produced from nuclear power plants or hydroelectric facilities. These two sources of electricity account for about 80% of the electricity generated in Canada today. Electricity produced from wind resources or small run of the river hydroelectric facilities would have very low GHG emissions similar to the emissions calculated from hydropower in the model. Hydrogen produced from this electricity would have very low emissions whether it was used in a fuel cell vehicle or an internal combustion engine. However, it is important to note that the GHG emissions benefit from hydrogen produced by electrolysis using these sources of electricity in the transportation sector is less than the GHG emission reductions that would occur if this electricity displace electricity produced by a coal powered facility.

The most energy efficient pathway is the diesel hybrid. The combination of the high efficiency engine combined with the hybrid drive train using a fuel with little conversion energy used in processing yields the lowest lifecycle energy use. This pathway is not currently available commercially and the challenge for the pathway is meeting the 2004 to 2007 particulate and NOx emission standards.

There is more stratification with the pathways studied for energy consumption than in the larger set looking at GHG emissions. The best hydrogen ICE consumes more energy than the gasoline baseline vehicle. The direct hydrogen pathways have better efficiency than the pathways that involve an energy carrier. All but four of the fuel cell pathways are better than the gasoline baseline vehicle. The four exceptions are all indirect pathways.

While it is beyond the scope of this work to examine the costs of hydrogen from each of the pathways the energy consumption data could be considered a rough proxy for the fuel costs per mile travelled. Since many of the forms of energy can be substituted for each other there is an approximate correlation between the energy consumed and the cost. This is not perfect since the substitution of one form of energy for another is not perfect but it can provide some guidance. Based on the energy results the use of hydrogen in an ICE is likely to be more costly than the use of gasoline even before the extra hydrogen specific cost issues are considered. Even the best hydrogen pathway is less energy efficient than a diesel hybrid and thus is likely to be more expensive. Again this is before any hydrogen specific cost issues are addressed.

When the relative rankings from the energy results and the GHG emission results are considered together it is noted that the coal to hydrogen pathways have some of the best energy efficiency results but the highest GHG results. This would suggest that coal may be one of the lowest cost methods of producing hydrogen but this pathway will produce only minimal GHG reductions when used in fuel cell vehicles and increases in GHG emissions if the hydrogen is used in internal combustion engines.

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1. INTRODUCTION

Under the Kyoto Protocol, Canada committed to reduce GHG emissions by 6% from 1990 levels by the period 2008 to 2012. The transportation sector represents the single largest source of Canada's GHG emissions, accounting for 27 per cent of the total. Transportation emissions arise from all sectors of the commercial economy and are inherent to the movement of people and goods for social and recreational activities. Hence, measures to reduce emissions from the transportation sector must be considered very carefully and respect the ramifications of such measures on the economy and peoples day-to-day activities. Emissions from transportation are growing faster than the average for all emissions and are forecast to exceed 1990 levels by 26 per cent in 2010 and 42 per cent by 2020.

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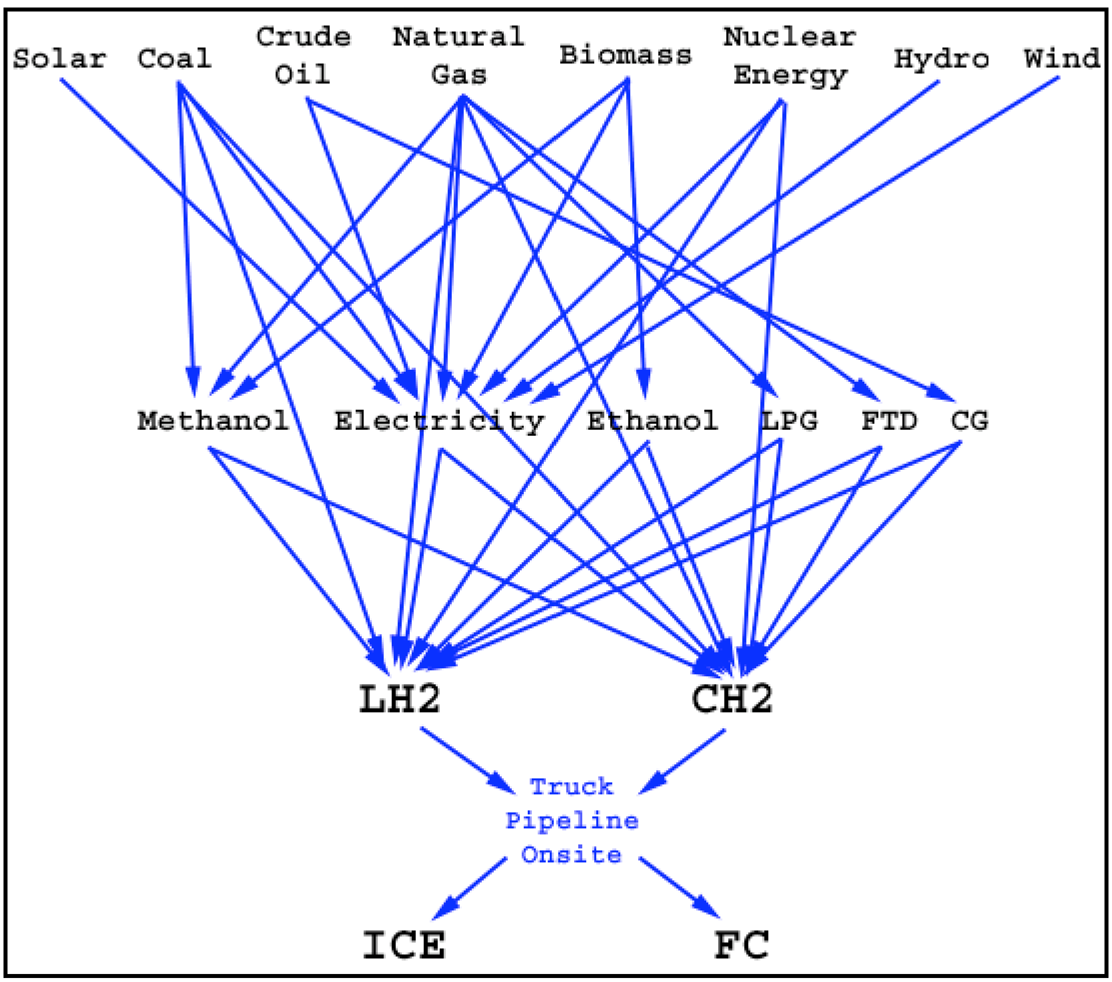

As this vision of a “Hydrogen Economy” evolves, more and more pathways are being identified. While some pathways will provide greenhouse gas benefits it is possible that others may not.

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> <u>Utilization</u>. The hydrogen could be used in an internal combustion engine or in a fuel cell. The data in GHGenius for the hydrogen ICE has been reviewed with a literature search to ensure that it is consistent with the latest developments in this area.

GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources. The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines for light duty vehicles, for class 8 heavy-duty trucks, for urban buses and for a combination of buses and trucks, and for light duty battery powered electric vehicles. There are over 80 vehicle and fuel combinations currently included in the model.

Some of the light duty internal combustion vehicles that the model is capable of analyzing include:

- Internal Combustion Engines
  - Conventional gasoline (including hybrids),
  - Low sulphur or reformulated gasoline (light duty or hybrid vehicles),
  - Diesel fuel (regular or low sulphur) including hybrids,
  - Hydrogen.
- Light duty fuel cell vehicles the fuels that the model is capable of analyzing include:
  - Methanol from natural gas, coal, or landfill gas reformed onboard the vehicle,
  - Any ethanol reformed onboard the vehicle,
  - Gasoline, or FTD reformed onboard the vehicle,
  - Hydrogen from electrolysis (compressed or liquefied),
  - Hydrogen from reforming natural gas, methanol, any ethanol, liquid petroleum gases, gasoline, FTD, coal, and biomass.
  - Hydrogen from nuclear thermo cracking of water,

Similar pathways are available for heavy-duty vehicles.

GHGenius can predict emissions for past, present and future years through to 2050 using historical data or correlations for changes in energy and process parameters with time that are stored in the model. 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 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 feedstock 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 fuel production 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 is not included if there is no fertilizer associated with the fuel pathway.
- Land use changes and cultivation associated with biomass derived fuels
  Emissions associated with the change in the land use in cultivation of crops, including N_2O from application of fertilizer, changes in soil carbon and biomass, methane emissions from soil and energy used for land cultivation.
- Carbon in Fuel from Air
  Carbon dioxide emissions credit arising from use of a renewable carbon source that obtains carbon from the air.
- Leaks and flaring of greenhouse gases associated with production of oil and gas
  Fugitive hydrocarbon emissions and flaring emissions associated with oil and gas production.
- Emissions displaced by co-products of alternative fuels
  Emissions displaced by co-products of various pathways. System expansion is used to determine displacement ratios for co-products from biomass pathways.
- 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. Includes lube oil production and losses from air conditioning systems.

GHGenius produces a wide range of outputs. The specific output data includes:

- CO_2-equivalent emissions (in g/mi) by stage of fuelcycle and for vehicle manufacture, for the feedstock/fuel/vehicle combinations identified above,
- Emissions (in g/mi) by individual pollutant for each stage of the fuelcycle for each feedstock/fuel,
- CO_2-equivalent emissions (in g/million BTU) for each stage of the upstream fuelcycle for each feedstock/fuel,
- BTU's of process and end-use energy per mile of travel by stage of lifecycle, for different feedstock/fuel/vehicle combinations,

Not all of the potential pathways shown in Figure 1-1 are currently in GHGenius but the model can be temporarily modified to produce all of the technically feasible pathways. The results for the hydrogen pathways studied have been ranked in terms of energy efficiency and greenhouse gas emissions. Several baseline pathways have been included to provide reference points for assessing the hydrogen pathways. These reference pathways include conventional gasoline, a gasoline hybrid vehicle, a diesel vehicle, a diesel hybrid vehicle and a natural gas vehicle.

All new innovations including the "Hydrogen Economy" have to provide multiple benefits to individuals and society in order to be adopted. In the case of hydrogen, certain pathways are unlikely to be adopted if they provide energy security benefits without reductions in greenhouse gas emissions and a positive benefit to cost ratio for the adopters. While it is beyond the scope of this work to evaluate the costs of the different hydrogen pathways it has been possible to compare the greenhouse gas emissions and energy balances of many of the hydrogen pathways on a common basis.

2. BASELINE VEHICLES

The analysis of the emissions and energy benefits of the hydrogen pathways are compared to several gasoline and diesel fuelled light duty vehicles. These vehicles are briefly described below.

2.1 CONVENTIONAL VEHICLES

Most of the vehicles operating today are powered directly by an internal combustion engine. In North America these are fuelled almost entirely by gasoline whereas in Europe there are many diesel powered vehicles and in some countries diesel is the largest selling fuel. Due to the higher thermal efficiency of diesel engines and with the improvements being made in exhaust emission performance of these engines there is increasing interest in this option in North America.

2.1.1 Gasoline

The analysis of the hydrogen pathways has been done for the year 2010 as that is likely the earliest date that high volume hydrogen vehicles would be available to the general public. The typical gasoline powered vehicle in 2010 is expected to achieve 10.65 L/100 km in city driving and 8.19 L/100 km in highway driving. Using a combination of 55% city driving and 45% highway driving the average in use fuel economy is 9.54 L/100 km. The curb weight of this vehicle is 1340 kg.

2.1.2 Diesel

The only diesel powered vehicles being offered in North America in 2003 are Volkswagens. They offer a number of vehicles with either a gasoline engine of a diesel engine. On average the diesel vehicles achieve 37.4%% better volumetric city fuel economy and 35% better highway fuel economy than their gasoline counterpart with the same transmission. This engine is a turbocharged direct injected (TDI) model. The engine produces more torque but less power than the gasoline version. The acceleration times are similar for both vehicles but the top speed is lower for the diesel version.

Not all diesel engine vehicles in the future may be the same specification as the Volkswagen TDI engine. A slightly lower relative fuel economy of 30% better than gasoline will be used for the modelling to account for this.

On this basis the equivalent typical diesel powered vehicle in 2010 is expected to achieve 7.45 L/100 km in city driving and 5.71 L/100 km in highway driving. Using a combination of 55% city driving and 45% highway driving the average in use fuel economy is 6.68 L/100 km. The curb weight of this diesel vehicle is assumed to be 1385 kg, 45 kg more than the gasoline equivalent.

2.1.3 Compressed Natural Gas

Compressed Natural Gas (CNG) has been used as a vehicle fuel in Canada and the United States for over 20 years. There are some similarities between CNG and hydrogen, both are compressed gases and both are clean burning, so CNG has been added as baseline vehicle for comparison purposes. Natural gas is also one of the likely feedstocks for hydrogen production.

Natural gas has a high octane rating (~130) compared to gasoline (87-91), which should allow the engine designers to use higher compression ratios and thus produce more efficient engines. In practice this has not occurred. Vehicle manufacturers must design for emissions, power, fuel economy, driveability and reasonable cost. In the case of CNG vehicles this has resulted in engines that are less efficient than gasoline vehicles.

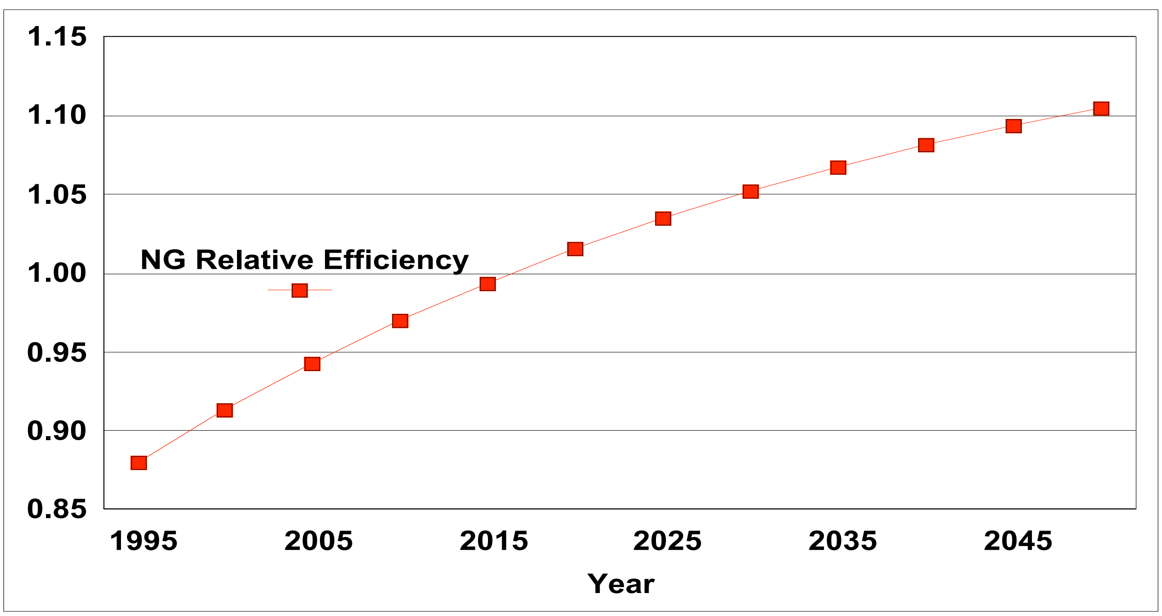
The relative efficiencies of a number of natural gas vehicles based on their EPA test data are shown in the following table. A gasoline vehicle has by definition a relative efficiency of 1.0. In the case of natural gas in GHGenius, with the high octane rating, the natural gas engines are projected to become more efficient over time as manufacturers design their engines to take advantage of the fuel properties.

Table 2-1 NGV Relative Vehicle Efficiencies

Vehicle	City Cycle	Highway Cycle	Combined (55/45)
2002 Crown Victoria	0.83	0.92	0.87
2001Ford E250	0.92	0.92	0.92
2003 Dodge Ram	0.93	0.94	0.93
2002 Honda Civic	0.97	0.89	0.93
2001 Toyota Camry	0.96	0.94	0.95
Average	0.92	0.92	0.92

The efficiency results over time are shown in the following figure. The relative efficiency results for the year 2002 are 0.92 and for the year 2010, the projection is 0.96. This 2010 value is used here.

Figure 2-1 Relative Efficiency Natural Gas LDV's



2.2 HYBRID VEHICLES

Hybrid vehicles are starting to be introduced to consumers. In 2003 vehicles are available from Toyota and Honda and in 2004 hybrid vehicles are expected to be available from Ford and several other manufacturers. There are many configurations that hybrid vehicles can take and the configuration has an impact on the relative fuel economy improvement that is achieved. The hybrid vehicles that are modelled are described briefly below.

2.2.1 Gasoline

The gasoline hybrid vehicle that is modelled is a relatively aggressive application of the hybrid technology. It achieves 1.79 times better engine efficiency in city driving and 1.3 times better efficiency in highway driving. This is typical of the performance benefits demonstrated by the Toyota Prius and the Honda Civic.

The vehicle has an extra weight for the batteries and other systems of 450 kg. The combined fuel economy is 1.52 times better than the gasoline powered internal combustion direct drive vehicle. The city fuel economy is 5.95 L/100 km and the highway fuel economy is 6.30 L/100 km. The combined fuel economy is 6.22 L/100 km.

2.2.2 Diesel

There are not yet any diesel hybrid vehicles being produced and sold. This is a viable future option if vehicle manufacturers wish to provide very high fuel economy vehicles in the future.

The diesel hybrid vehicle that is modelled is similar to the gasoline version and is a relatively aggressive application of the hybrid technology. It achieves 1.79 times better engine efficiency in city driving and 1.3 times better efficiency in highway driving than the diesel vehicle. The vehicle has an extra weight for the batteries and other systems of 450 kg. The combined fuel economy is 1.52 times better than the diesel powered internal combustion direct drive vehicle. The city fuel economy is 4.16 L/100 km and the highway fuel economy is 4.39 L/100 km. The combined fuel economy is 4.26 L/100 km. Compared to the standard gasoline powered vehicle the diesel hybrid has 2.17 times better fuel economy.

The fuel economy characteristics of the four baseline vehicles are compared in the following table.

Table 2-2 Fuel Economy of the Baseline Vehicles

	City		Highway		Combined	
	L/100 km	Relative Efficiency	L/100 km	Relative Efficiency	L/100 km	Relative Efficiency
Gasoline	10.65	1.0	8.19	1.0	9.54	1.0
Gasoline Hybrid	5.95	1.79	6.30	1.3	6.22	1.53
Diesel	7.45	1.29	5.71	1.29	6.68	1.29
Diesel hybrid	4.16	2.31	4.39	1.68	4.38	1.97

3. HYDROGEN PRODUCTION

One of the advantages of hydrogen as a fuel is the number of ways that it can be produced. There are 45 hydrogen scenarios considered in this report when the variations in the form of hydrogen (liquid or compressed) and the location (central or decentralized) are considered. There are also five non-hydrogen baseline scenarios developed for comparison. In this section the parameters for each of the hydrogen production methods are briefly described along with a brief description of liquefaction and compression. In the section 4 of the report hydrogen delivery is described.

In this section hydrogen production is broken down into direct and indirect pathways. The direct pathways take the energy resource and convert it directly to hydrogen. The indirect pathways produce an energy carrier from the energy resource and then produce the hydrogen from the energy carrier.

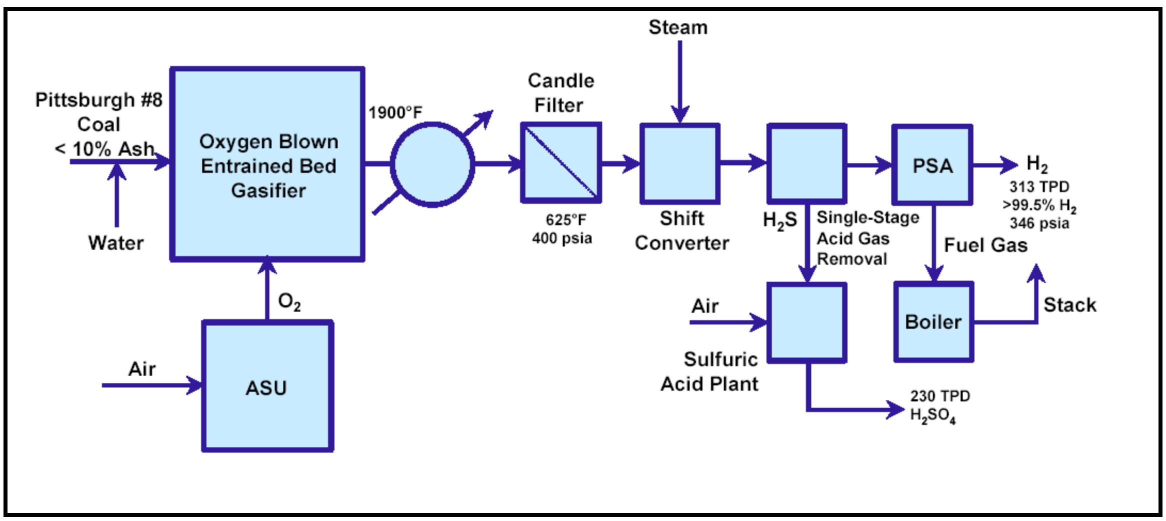
3.1 DIRECT PATHWAYS

There are four direct pathways that are considered here and several variations of each pathway to produce a total of 18 scenarios. Each of the four pathways and its variations are described below.

3.1.1 Coal to Hydrogen

The concept of the conversion of coal to hydrogen is to first gasify the coal to produce hydrogen, carbon monoxide and carbon dioxide, the carbon monoxide is shifted to produce more hydrogen and carbon dioxide and then there is a purification step to concentrate the hydrogen. The typical flow process is shown in the following figure (US DOE, 2002).

Figure 3-1 Coal to Hydrogen Block Flow Diagram



There are several different production concepts that are being sold or developed. There are different manufacturers of the gasifiers themselves including Texaco, E-Gas and Shell. There are also different concepts being developed for the gas clean-up stages, including some that are very energy efficient.

Two hydrogen production concepts were found in the literature that use existing commercial technology and have fully developed mass balances. The first system uses a Texaco quench gasifier, conventional cold cleaning, water gas shift, and pressure swing adsorption with no carbon dioxide sequestration. This system was reviewed for the US DOE as the baseline for the study of advanced membrane technologies (Mitretek, 2002). The second system was described by Parsons for the US DOE (US DOE, 2002); it uses an E-Gas gasifier and conventional gas clean-up trains. The characteristics of each system are summarized in the following table.

Table 3-1 Coal to Hydrogen Systems

	Texaco Gasifier	E-Gas Gasifier
Coal Consumed	3000 T/D	2500 T/D
Coal Quality	12,450 BTU/lb.	12,450 BTU/lb.
Hydrogen Produced	131 MMSCFD	112 MMSCFD
Excess Power Produced	20.4 MW	38 MW
Coal Consumed per million BTU Hydrogen	135.5 lb.	132 lb.
Excess Electricity produced per million BTU Hydrogen	11 kWh	24 kWh
Cold Gas Efficiency	59.3%	59.9
Overall Efficiency	63.0 %	64.4%

The Texaco gasifier has more installations around the world so that is the system that is modeled here. One adjustment that must be made is to adjust the coal quality to a typical Canadian coal energy content of 10,061 BTU/lb, so the coal feed rate has been increased from 135.5 pounds to 167.7 pounds per million BTU of hydrogen to maintain the same energy efficiency as in the above table.

It has been assumed that the hydrogen production facilities will be central plants that will be located close to the distribution and use of the hydrogen. Transporting the coal over long distances is more efficient than transporting hydrogen. In the model, the coal is transported an average of 1700 miles by rail. Both a liquid hydrogen and compressed hydrogen scenario is examined for the final distribution of the hydrogen to the dispensing location. The distances assumed for all of the central systems is discussed in Section 4. There will therefore be two coal to hydrogen scenarios.

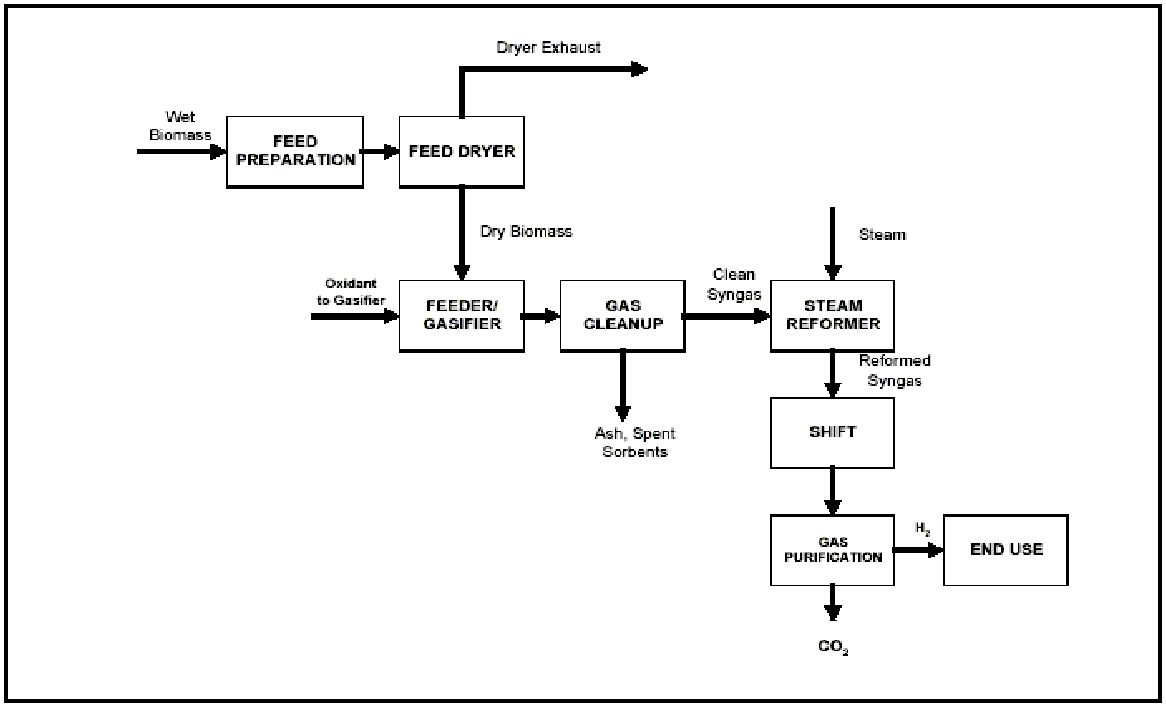
3.1.2 Wood to Hydrogen

The production of hydrogen from biomass follows the same general process as that of coal to hydrogen. The biomass is first gasified, the gas is treated to increase the hydrogen content and then the hydrogen is purified. The syngas produced from biomass gasification can contain a number of contaminants including particulates, tars, sulphur and chlorine compounds. The syngas may also contain significant quantities of methane, which must be reformed to more syngas, depending on the composition of the feedstock and the type of gasifier used.

In a recent report prepared for the US DOE by E^2S (2002) biomass gasification technologies were benchmarked for the production of fuels, chemicals and hydrogen. They concluded that for hydrogen production it would be desirable to have a gas that had a high hydrogen to carbon monoxide ratio, low hydrocarbon levels, low nitrogen content, high water content and have a temperature of 100-200°C at the exit. This report compared the operating characteristics of a large number of gasifiers and concluded that bubbling fluidized bed gasifiers for the production of fuels, chemicals and hydrogen applications currently have an advantage over other types of gasifiers.

An example of a bubbling fluidized bed gasifier is the one developed by the Gas Technology Institute and its predecessor the Institute of Gas Technology. The block for diagram for the biomass to hydrogen technology is shown in the following figure. This gasification technology has been demonstrated at the 11 tonne per day level producing synthesis gas for combustion. The technology has not been demonstrated for the production of hydrogen.

Figure 3-2 Biomass to Hydrogen



In spite of the lack of an actual demonstration of the technology, there have been a number of techno-economic studies performed on the production of hydrogen from biomass (Spath et al, 2000, Lau et al, 2002, Hamelinck et al, 2001). There are many different configurations that could be devised for biomass to hydrogen systems. Most, but not all produce hydrogen and some electricity and the ratio of the two products can vary with different configurations. For the base modelling case, the work of Hamelinck will be used as their published work has the most complete mass and energy balance of all of the studies. Of the five variations of the biomass to hydrogen process that they studied, three used an IGT gasifier and one configuration was designed for maximum hydrogen production. The inputs and outputs required for this process are summarized in the following table. The electrical requirements are the net requirements after the electricity produced by the process and the total process demands are considered. The wood required as the input must have a moisture content of less than 30% in this case. The thermal efficiency for this case is about 60%, which is comparable to that reported in several of the other studies.

Table 3-2 Mass and Energy Inputs for Hydrogen from Biomass

	Plant	Model Inputs
Hydrogen Produced	259 MW_{th}	1 million BTU
Biomass Input	430 MW_{th}	198.9 lbs.
Electricity Required	1 MW	1.13 kWh

The wood requirements (feedstock) for the gasifier are assumed to be grown in a short rotation forestry system. The hydrogen production facility will be a centralized system with hydrogen distribution by truck in either a liquid or compressed gas form. Therefore there are two wood to hydrogen scenarios considered.

3.1.3 Natural Gas to Hydrogen

Most of the world's hydrogen is produced by reforming natural gas. This concept can be used both in large scale centralized plants and in small onsite reformers. Both scenarios are considered here.

There is a range of efficiencies of steam methane reformers available from many of the systems manufacturers around the world. The systems can be designed for site specific needs and costs. The energy requirements for these systems is summarized in the following table ((S&T)^2, 2003).

Table 3-3 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[1]	Thomas et al.
BOC	1260	12.7[1]	Thomas et al.

The specific case modeled will be 1387 SCF of natural gas (1000 BTU/SCF) and 2.43 kWh of electricity plus the electricity for compression per million BTU of hydrogen in the year 2010.

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 in 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. Note that this is not significantly different than the energy range of the small plants. The same energy requirements for large and small plants are modelled here.

For the large centralized plants distribution in both a liquid and compressed form is considered. There are therefore a total of three scenarios considered for natural gas to hydrogen pathways.

[1] Includes compression energy.

3.1.4 Thermonuclear Hydrogen Production

Thermochemical water splitting processes have been studied for the past 35 years (Besenbruch, et al). They were extensively studied in the 1970's and 80's but have not received much attention for the past ten years. There have been over 100 cycles proposed but substantial research has been undertaken on only a few. In 1999 General Atomics in collaboration with the University of Kentucky and Sandia National Laboratories undertook an exhaustive literature search to identify all of the cycles previously proposed and then screened them to determine which of the cycles could benefit in terms of efficiency and cost from high temperature advanced nuclear reactors. These advanced nuclear reactors are not expected to be in service until 2030. Two cycles were selected from this screening process, the adiabatic UT-3 cycle invented at the University of Tokyo and the sulphur-iodine cycle.

These systems, if they are built, will be large centralized producers of hydrogen. There will be greenhouse gas emissions associated with the production and transportation of uranium and emissions associated with the liquefaction or compression of the hydrogen and its distribution.

The emissions from the uranium part of the cycle are calculated based on the relative efficiency of these cycles versus the 33% efficiency of existing nuclear plants converting steam to electricity. Since both of these cycles are projected to have a higher efficiency, these emissions will be lower. The efficiency of the sulphur-iodine cycle is expected to be about 50% and this is the system modelled here.

Two scenarios using liquid hydrogen and compressed hydrogen are considered. It is assumed that if nuclear reactors are used to produce hydrogen then other nuclear reactors may also be built to produce electricity, which is used for the liquefaction and compression systems.

3.2 INDIRECT PATHWAYS

Hydrogen can also be produced through an indirect pathway such as electrolysis or reforming a refined fuel. Twenty-six of these pathways are considered here. All of these indirect pathways could be implemented at a small scale at the dispensing site so no transportation requirement for the hydrogen is considered here. The use of the hydrogen onsite offsets some of the losses in energy efficiency that result from refining the indirect fuel. These indirect pathways and the assumptions used to define them are described in the following sections.

3.2.1 Electrolysis

The electrolysis of water is commonly used to produce hydrogen, especially at relatively small scale. Many producers of electrolysers are actively pursuing the development of systems to supply hydrogen to the transportation sector. In GHGenius the efficiency of the electrolyzer in the year 2010 is 81.16% and it requires 48.55 kWh of electricity to produce one kilogram of hydrogen. The electricity required to compress the gas is calculated separately.

The emissions from this hydrogen pathway are strongly influenced by how the hydrogen is produced. There are of course many ways to produce electricity and in all regions of Canada several electricity production pathways are used to supply all of the electricity requirements. Since the use of hydrogen for transportation requirements represents new demand for electricity it is the incremental source of electricity that is of the most interest. In most regions of the country the incremental source of electricity is combined cycle natural gas systems but in some regions coal may be the incremental source. In Manitoba hydroelectricity is likely the incremental source of power. In GHGenius hydroelectricity is also a good proxy for the greenhouse gas emissions for electricity produced from wind power or even solar power. There are also advocates of increased nuclear generation of electricity to reduce greenhouse gas emissions. All of these incremental electricity sources are modelled along with the Canadian average mix of electricity expected in 2010.

3.2.1.1 Average Mix

The average mix of electricity production in Canada is shown in the following table.

Table 3-4 2010 Electricity Mix – Canada

Source	Efficiency	% of Total
Coal	34.4%	17.0
Oil	35.1%	0.0
Gas Boiler	37.7%	1.7
Combined Cycle Gas	50.0%	1.2
Nuclear	-	21.3
Hydro	-	58.8

The greenhouse gas emission intensity of this mix of electricity delivered to the end use is 63,066 grams/million BTU of power.

3.2.1.2 Electricity from Coal

Coal fired electricity may be the incremental source of power in some regions of the country. The efficiency of the coal fired power stations is as shown in the previous table. The greenhouse gas emission intensity of this mix of electricity delivered to the end use is 313,123 grams/million BTU of power. This is about five times the emission intensity of the average mix.

3.2.1.3 Electricity from Combined Cycle Natural Gas

Electricity produced from natural gas in combined cycle power plants has been added to the power mix in recent years. These plants have a higher thermal efficiency than coal plants and have a greenhouse gas emission intensity delivered to the end use of 138,427 grams/million BTU of power.

3.2.1.4 Electricity from Nuclear Power

Nuclear power produces very low emissions of greenhouse gases. The emissions are mostly related to the transportation and enrichment of the uranium ore and N_20 emissions from the distribution system. The greenhouse gas emission intensity of this mix of electricity delivered to the end use is 3,789 grams/million BTU of power.

3.2.1.5 Electricity from Hydropower

Some regions of Canada such as Manitoba still have undeveloped hydroelectricity potential. The greenhouse gas emission intensity of this mix of electricity delivered to the end use is

7,172 grams/million BTU of power. Emissions are related to methane and carbon dioxide emissions from reservoirs and N_20 emissions from the distribution system.

The following table summarizes the GHG emissions for the various sources of electricity.

Table 3-5 GHG Emissions from Electricity Production

Source	% of Total	GHG Emissions, grams/million BTU power
Coal	17.0	313,123
Gas Boiler	1.7	182,377
Combined Cycle Gas	1.2	138,427
Nuclear	21.3	3,789
Hydro	58.8	7,172
Average Mix	100	63,066

3.2.2 Methanol to Hydrogen

Methanol can be reformed to hydrogen and carbon dioxide at relatively low temperatures of about 300 ^{o}C. This lower temperature offers a distinct advantage over reforming natural gas. Low temperature operation permits for fast start up, a simplified process flow and the use of inexpensive materials of construction. The systems have higher efficiencies, typically on the order of 80% compared to the 67 to 70% efficiency of steam methane reforming units.

There are a number of manufacturers of these systems. In Germany, Caloric Analgenbau GmbH, and Mahler AGS GmbH both manufacture hydrogen production units using methanol decomposition. Other European companies with systems include Axsia Howmar Hydrogen Division, an English company and Haldor Topsoe a Danish company. In the United States Hydro Chem, a subsidiary of Linde, produce packaged systems. All of these manufacturers also produce hydrogen units based on SMR of methane.

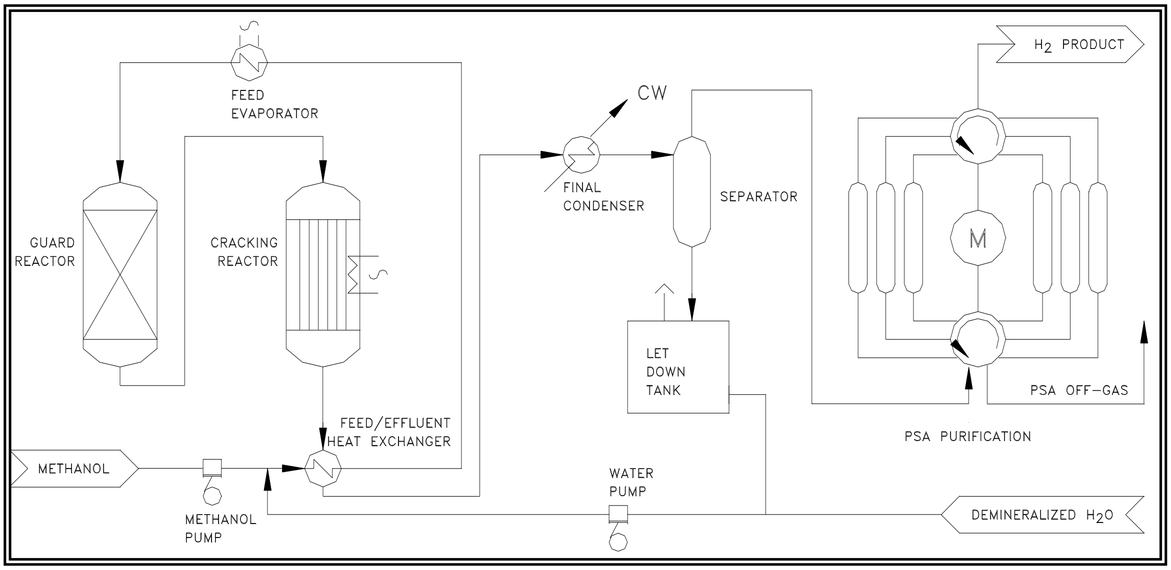
Methanol decomposition is regularly used to provide hydrogen for industrial applications such as hydrogenation of edible oils and fatty acids and in the manufacture of electronic components and plate glass.

The basic process of methanol decomposition, in the following figure, consists of the following steps:

- Mixing of methanol and demineralized water.
- Preheating and evaporation of the methanol/water mixture.
- Methanol decomposition and shift conversion.
- Process gas cooling and condensate separation.
- Purification in PSA unit.

This is sometimes incorrectly referred to as steam reforming of methanol. It differs from the other steam reforming processes described later by not requiring steam for the first step in the process. The steam or water is only required for the water gas shift of carbon monoxide to hydrogen.

Figure 3-3   Methanol to Hydrogen Reformers



For systems up to 150 NM^3/hr (325 kg/day) the PSA purge gases are catalytically combusted to supply the required energy and they are electrically heated for the remainder of the energy requirements. The larger systems up to 3,000 NM^3/hr (6500 kg/day) are fuelled by the PSA purge gases and methanol. The operating parameters are shown in the following table for typical systems. The larger system has been used as the basis for the modeling. The methanol fuel could also be supplied by other energy sources such as natural gas depending on the site requirements.

Table 3-6   Methanol Reformer Operating Requirements

	Methanol Feed	Methanol Fuel	Electric Power	Cooling Water
	Kg/NM^3 H_2	Kg/NM^3 H_2	kWh/NM^3 H_2	litres/ NM^3 H_2
Small Systems	0.67	0	0.45	20
Large Systems	0.63	0.06	0.06	20
	USG/million BTU	USG/million BTU	kWh/million BTU	USG/million BTU
Small Systems	18.57	0	37.25	1,655
Large Systems	17.46	1.66	4.97	1,655

The systems offered by different suppliers are quite close in their performance especially for the larger systems. The input values shown above for the large systems have been used for this work.

3.2.3 Ethanol to Hydrogen

Ethanol is not reformed to hydrogen commercially. It has been used in some of the US DOE research programs developing multi-fuel reformers and a 15 kW stationary fuel cell system is under development. The project partners announced they have recently completed the design phase. Caterpillar, Inc., Nuvera Fuel Cells, Inc., and Williams Bio-Energy have teamed up to design, build, and operate a 13 kilowatt stationary fuel cell that will be powered by hydrogen derived from ethanol (RFA).

The likely reasons for no commercial hydrogen production from ethanol relates to the fact that it is traditionally a more expense feedstock than methanol, methane or LPG and it is more technically challenging. Although ethanol and methanol both are alcohols, there is a great difference in their chemical behaviour. Ethanol will, instead of decomposing, dehydrate into the unsaturated chemical ethylene which needs to be saturated (requiring the consumption of hydrogen) turning into ethane which then can be reformed and produce hydrogen.

Ethanol reforms at lower temperatures than methane or LPG but higher temperatures than methanol. The Nuvera ethanol system uses an auto thermal reactor.

The system requirements for a stationary ethanol to hydrogen system have been estimated so that the overall system efficiency is in line with values reported by Epyx (a Nuvera predecessor company) to the US DOE (US DOE 1999). From the efficiency for ethanol, the utility consumption in the next table has been calculated. These values are used as the default values for this work.

Table 3-7 Utility Consumption Ethanol Reformers

Input	Consumption	Consumption
Ethanol	0.61 kg/NM^3	16.91 USG/million BTU
Ethanol for steam	0.12 kg/NM^3	3.75 USG/million BTU
Electricity	0.30 kWh/NM^3	25 kWh/million BTU
Cooling water	100 litres/NM^3	2190 USG/million BTU

The ethanol could be produced from a variety of feedstocks. Two are considered here, agricultural residues (grass or straw) and wheat. Canada has significant resources of each material that could be used for large scale ethanol production. Ethanol is also produced from corn in Canada and the GHG emissions from corn ethanol are typically slightly lower than the emissions from wheat ethanol.

3.2.4 LPG to Hydrogen

LPG (propane) can be steam reformed to hydrogen in much the same as methane can be reformed. Relatively small-scale systems (50-400 NM^3/hr) have been built by companies such as Mahler, Caloric, Haldor Topsoe, and Hydro-Chem. These systems are ideally sized for the expected hydrogen loads of a typical service station in a mature marketplace.

LPG is preheated to about 380 ^oC before passing through a cobalt molybdenum catalyst and zinc oxide bed to desulphurize the gas. Steam is mixed with this gas, preheated to 480 ^oC and introduced in to a nickel catalyst reformer to produce carbon monoxide and hydrogen (first reaction). The gas leaves the reactor at 800 ^oC and is then cooled to approximately 350 ^oC and introduced into a second reactor (iron catalyst) to convert the carbon monoxide and steam to more hydrogen and carbon dioxide (second reaction). The gas is finally purified to 99.9995% hydrogen in a pressure swing absorption unit. Note that unlike the methanol decomposition systems the two reactions occur at different temperatures and in different reactors. The process is shown in the following figure.

$$C_3H_8 + 3H_2O \rightarrow 3CO + 7H_2$$

$$3CO + 3H_2O \rightarrow 3CO_2 + 3H_2$$

The overall reaction becomes;

$$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 10H_2$$

The utility consumption of a unit manufactured by Mahler is shown in the following table. These are the default values in the model. It is assumed that the steam required for the process is produced from the combustion of propane at an efficiency of 80%. In this system, the PSA purge gas is recycled to the fuel inlet of the reformer furnace.

Table 3-8 Utility Consumption LPG Reformers

Input	Consumption	Consumption
LPG	0.40 kg/NM^3	17.26 USG/million BTU
LPG for steam	0.081 kg/NM^3	3.50 USG/million BTU
Electricity	0.32 kWh/NM^3	26.5 kWh/million BTU
Cooling water	100 litres/NM^3	2190 USG/million BTU

3.2.5 FT Distillate to Hydrogen

Distillates and heavy fuel oils have been successfully used as feedstocks for hydrogen production plants in oil refineries and similar facilities. Approximately 30% of the world's production of hydrogen is derived from petroleum feedstocks.

Fischer Tropsch distillates are attractive fuels for reforming since they are sulphur free and have a rather narrow composition range. Experiments with reforming these fuels have been performed by Syntroleum Corporation. Much of this work has been on a naphtha type material that would be similar to the gasoline step modeled. Very little actual data is available.

Based on the performance data from the Epyx auto thermal reactor the system requirements for a FT distillate have been estimated. The assumptions are shown in the following table and they have been used as the default values.

Table 3-9 Utility Consumption FT Distillate Reformers

Input	Consumption	Consumption
FT Distillate	0.41 kg/NM^3	11.57 USG/million BTU
FT Distillate for steam	0.08 kg/NM^3	2.56 USG/million BTU
Electricity	0.31 kWh/NM^3	26.6 kWh/million BTU
Cooling water	100 litres/NM^3	2190 USG/million BTU

3.2.6 Gasoline to Hydrogen

Gasoline reformers are being developed for use on board fuel cell vehicles. Gasoline could also be reformed at a service station and compressed hydrogen dispensed to the vehicle. Gasoline reformers are not commercially available but several manufacturers of hydrogen production systems do offer naphtha systems. These systems have been sold by Mahler, Caloric, Haldor Topsoe and Hydro Chem.

Naphtha reformers operate essentially the same as LPG reformers with similar catalysts and temperatures. It is assumed that gasoline would be reformed in a similar manner. If octane (C_8H_{18}) is a surrogate for gasoline then the reactions are as follows.

$$C_8H_{18} + 8H_2O \rightarrow 8CO + 17H_2$$

$$8CO + 8H_2O \rightarrow 8CO_2 + 8H_2$$

The overall reaction is;

$$C_8H_{18} + 16H_2O \rightarrow 8CO_2 + 25H_2$$

The utility consumption of a unit is estimated from the requirements of a Mahler naphtha reforming system and is shown in the following table. These are the default values in the model. It is assumed that the steam required for the process is produced from the combustion of gasoline at an efficiency of 80%. In this system, the PSA purge gas is recycled to the fuel inlet of the reformer furnace.

Table 3-10 Utility Consumption Gasoline Reformers

Input	Consumption	Consumption
Gasoline	0.42 kg/NM^3	12.43 USG/million BTU
Gasoline for steam	0.093 kg/NM^3	2.75 USG/million BTU
Electricity	0.33 kWh/NM^3	27.3 kWh/million BTU
Cooling water	105 litres/NM^3	2300 USG/million BTU

3.3 Hydrogen Liquefaction

For the liquid hydrogen option it is assumed that all of the energy requirements are supplied by electricity. The energy requirements are large in part because liquid hydrogen must be stored at a very low temperature (-253 ^{o}C). In GHGenius it is assumed that 26% of the energy contained in LH_2 is required to liquefy the gas in large-scale plants. These values can be compared to other values found in the literature. 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 (2003) reports efficiencies of 74% for large central facilities and 69% for small remote locations.

Fuel leakage or boil-off rates for hydrogen are assumed to be 4% per transfer and that 3 transfers are required. A transfer is a movement of the product from one vessel to another where the vessels are not permanently connected to each other. For example, moving liquid hydrogen from a central facility to a service station would have two transfers, one from the facility to the transport truck and the second from the truck to the service station. Moving the product from the service station tank to the vehicle would be a third transfer. It is further assumed that some of the gas lost through boiloff is captured and reliquefied. For the year 2010 the energy requirements for liquid hydrogen (after considering the losses and reliquefaction) amount to 27.1% of the energy in the delivered hydrogen. The assumptions that are included in GHGenius for liquefaction of natural gas and hydrogen are summarized in the following table.

Table 3-11 Assumptions for Liquefaction of Hydrogen

	LH_2
BTUs process energy per BTU fuel processed, small scale, at refueling site	0.330
BTUs process energy per BTU fuel processed, large scale, at central site	0.260
Fraction of process energy from electricity	n.a.
Fuel leakage or boil-off, per fuel transfer, in a base year (% of net output to consumers)	4.00%
Number of transfers, small scale, at refueling site	1
Number of transfers, large scale, at central site	3
Base year of fuel-leakage or boil-off	1995
The annual % change in leakage or boil-off	-7.0%
Of fuel boiled-off, the fraction reliquefied	50%

3.4 HYDROGEN COMPRESSION

The energy requirements for compressing hydrogen are substantial. GHGenius uses an adiabatic compression cycle with an inlet pressure of 100 psi and a storage pressure of 5,500 psi. Electric motors are used to drive the compressor and the energy consumed is 6.5% of the energy delivered in the fuel. A 1% leakage rate is assumed. Higher hydrogen pressures of 10,000 psi are also being considered. In this case the energy consumption would be 8.8% of the energy delivered in the fuel. The assumptions for compressed hydrogen (at 5,500 psi) are summarized in the following table.

Table 3-12 Compressed Hydrogen Assumptions

	CH_2
BTUs compression energy per BTU fuel processed at refueling site	0.067
Fraction of compression energy from electricity	1.0
Fuel leakage in base year (% of net output to consumers)	0.07%
Number of transfers at refueling site	1
Base year of fuel-leakage or boil-off	1995
The annual % change in leakage	-1.0%

4. HYDROGEN DELIVERY

The low density of hydrogen makes the transportation of hydrogen a challenge. Today hydrogen is moved by pipeline in a few locations around the world. It is also liquefied to increase the density to make the truck transportation more realistic and feasible for longer distances. There is also work underway to increase the pressure that compressed hydrogen can be stored and transported at to improve the feasibility of that supply option. The volumetric density of hydrogen in various forms is summarized and compared to gasoline in the following table.

Table 4-1 Hydrogen Density

	Compressed Hydrogen, 5,000 psi	Compressed Hydrogen, 10,000 psi	Liquid Hydrogen	Gasoline
Weight of 1 M^3	23 kg	40 kg	71 kg	730 kg
Energy of 1 M^3, million BTU	3.09	5.37	9.53	32.12

4.1 ONSITE PRODUCTION

Onsite production of hydrogen is the simplest scenario to model since there is no extra energy required to move the product. This scenario does require that the hydrogen production method is applicable to onsite production. There are a number of pathways where this is unlikely to be feasible such as hydrogen from coal, wood or the thermonuclear cracking of water. For these pathways it is assumed that the hydrogen is produced at a central site and shipped to the dispensing location.

There may be economic reasons for building central plants since there are economies of scale involved with hydrogen plant capital costs. At least a portion of the savings gained from large plants will be used to offset the transportation costs. From the perspective of energy balances and greenhouse gas emissions there are no significant savings achievable with central plants so these scenarios usually have higher emissions and less attractive energy balances than onsite systems. It will be assumed that all systems except the three mentioned above will be onsite systems.

4.2 PIPELINES

Hydrogen can be moved by pipeline where there are sufficient volumes to do so economically. In this work it is assumed that demand for hydrogen in 2010 will not be large enough to justify hydrogen pipeline systems.

4.3 LIQUID HYDROGEN

Linde (1997) state that they have liquid hydrogen transportation containers available with volumetric capacities of 15,000, 41,000 and 53,000 litres. The largest container has a capacity similar to that of gasoline transportation trucks in Canada and the middle size is similar to gasoline trucks in the US. The weight of hydrogen transported in each of these containers is only 1,000, 2,900 and 3,750 kg respectively. The weight of gasoline transported in a similar size of truck is an order of magnitude higher.

The difference in the payload weight has a large impact on the energy required to transport the fuel. The fuel that is consumed in delivering a load of fuel to the customer is a function of the total mass moved and the distance travelled (a round trip). The fuel consumed therefore moves the weight of the truck both ways and the weight of the delivered fuel one way. If the weight of the truck and trailer is 40,000 kg then the weight of liquid hydrogen contributes to only about 4.5% of the total fuel consumed whereas the gasoline contributes to about 30% of the fuel consumed. The energy consumption for hydrogen is therefore 666% of that of gasoline on a BTU/Ton-mile basis.

Amos (1998) details the costs of storing and transporting hydrogen. In his transportation cost assumptions, he assumed that a truck could deliver 4,082 kg of liquid hydrogen and that the truck averaged 6 miles per gallon for the round trip. This is equivalent to 9,280 BTU/Ton-mile based on the one-way distance that GHGenius uses. This is 475% of the value that is used for the transport of light petroleum products.

The value for the extra energy that has been used for version 2.3 of GHGenius is 400% based on these two examples. The total energy required is therefore five times that for light petroleum products. It is assumed that not all liquid hydrogen trucks will be as large as Amos has assumed and that his estimate represents a best case scenario rather than an average scenario. This same value will be used for rail and shipment movements of liquid hydrogen. This probably overestimates the energy required for these modes but very little liquid hydrogen is moved by rail or barge today and these are not likely to be significant transportation modes in the near future.

The values for liquid hydrogen transportation that have been used for the scenarios here are that 100% of the hydrogen is transported by truck an average of 150 miles. The energy required for the shipment of the liquid hydrogen represents 1.44% of the energy stored in the hydrogen. The combined energy requirement for liquefaction and delivery is 28.5% of the energy in the hydrogen at the nozzle.

4.4 COMPRESSED HYDROGEN

Compressed hydrogen faces similar but even larger transportation challenges than liquid hydrogen due to its even lower density. Linde have steel tanker trucks for compressed hydrogen that are capable of a theoretical capacity of 300 kg and composite fibre wrapped flasks that can theoretically move 500 kg. Linde note that the effective capacity is less due to the pressure equalization of the customer tanks.

Amos assumed that 181 kg (400 pounds) could be transported by truck. Eliasson et al (2002) note that compressed hydrogen trucks in Europe can transport about 320 kg of hydrogen at 3000 psi and that about 80% of that can be delivered to the customer. With technical developments they estimate that it should be possible to deliver 400 kg to a customer.

The energy requirements for truck transportation calculated by Amos are 22.6 times higher than that for liquid hydrogen or 210,400 BTU/Ton-mile. This is 108 times higher than the energy required for light petroleum products. Eliasson calculate that the energy requirement for compressed hydrogen is 48 times that of light petroleum products. The two values are actually quite close when the different quantities of hydrogen that each move are considered.

It is assumed that if hydrogen as a vehicle fuel is adopted and compressed hydrogen is moved by truck that there will be developments of the tanks so that 400 kg can be transported at a time. The value for extra energy that has been used for the model is therefore set at 50 times that of petroleum products. This value is extremely sensitive to the weight of hydrogen that can be transported.

The values for compressed hydrogen are that 100% of the hydrogen is transported by truck a distance of 150 miles. This is the same scenario as that for liquid hydrogen for comparison purposes. The energy required for the shipment of the compressed hydrogen represents 11.76% of the energy stored in the hydrogen. The combined energy requirement for compression and delivery is 18.5% of the energy in the hydrogen at the nozzle.

The following table summarizes the transportation energy requirements for liquid and compressed hydrogen.

Table 4-2 Summary of Transportation Energy Requirements

	Liquid Hydrogen	Compressed Hydrogen
Payload, kg	4,000	400
Transport mode	Truck	Truck
Transportation distance, miles	150	150
Energy consumed in transport as a function of energy delivered to consumer, %	1.44%	11.76%
Combined energy consumed, liquefaction or compression plus transportation, %	28.5	18.5

5. HYDROGEN USE

The recent interest in the Hydrogen Economy has coincided with the rapid development of the fuel cell and the interest in the fuel cell by the major automobile manufacturers around the world. In the past couple of years it has become apparent that fuel cell vehicles would not be introduced to the market place as early some people had predicated and more thought is being given to the real challenge of introducing a new fuel and vehicle at the same time. These factors have lead to the consideration of hydrogen as a fuel for internal combustion engines. The relative theoretical and actual efficiencies of the internal combustion engine and the fuel cell engine are significantly different.

Any interim steps to introduce hydrogen into the transportation fuel mix need to be carefully considered. There is still significant development of fuel cells required before they can be successfully introduced into the market. If some of the existing challenges cannot be overcome then they may never be adopted for technical or economic reasons. The interim steps taken to develop a hydrogen market should be able to stand on their own merit since otherwise they risk becoming stranded investments.

In the next sections the use of hydrogen in internal combustion engines and in fuel cells is discussed with particular focus on the expected performance in 2010.

5.1 INTERNAL COMBUSTION ENGINE

With the slower development of the fuel cell vehicle than earlier projected it has been suggested that using hydrogen in an internal combustion engine is a way to bridge the hydrogen supply infrastructure gap. This could be accomplished by using blends of hydrogen and natural gas (Hythane) or using 100% hydrogen in the engine.

5.1.1 Hythane®

Hythane® is a registered trademark for a blend of hydrogen and natural gas. In Canada, the trademark is owned by the Quebec government and in the US; the owner is Hydrogen Components Inc. Other participants in the field refer to mixtures of the two gases as HCNG (hydrogen enriched compressed natural gas). Research into Hythane® has been going on for about 30 years and there have been several demonstrations of the technology over the years. Data from these demonstrations have been used in the modeling wherever possible.

Supplementation of hydrogen into natural gas (Hythane® or HCNG) extends the lean-burn, or charge-dilution limit of combustion in engines. Extremely low oxides of nitrogen (NOx) and carbon monoxide (CO) emissions can be achieved when a combined lean-burn and exhaust gas recirculation (EGR) combustion strategy is employed with Hythane®. The excess air from lean-burn can be used to reduce CO and non-methane hydrocarbons with an oxidation catalyst. The EGR is intended to be the primary charge dilution agent to reduce peak combustion temperatures thus leading to extremely low NOx emissions.

Without the hydrogen enhancement, natural gas would not be able to combust with the amount of charge dilution necessary to achieve extremely low NOx emissions without sacrifices in fuel consumption, torque fluctuation, and hydrocarbon emissions. Hydrogen itself is not considered a low NOx fuel. Due to higher combustion temperatures than natural gas at equivalent air/fuel ratios, hydrogen actually produces higher NOx emissions. It is important that the hydrogen supplementation be significant enough to extend the charge-dilution limit to levels sufficient to reduce NOx emissions beyond what is capable with three-way catalyst technology at stoichiometric air/fuel ratios. Some developers have been able to achieve this with 20 vol % hydrogen and others recommend at least 30 vol % hydrogen to consistently achieve improvements in NOx emissions compared to natural gas alone with catalytic exhaust after treatment.

The engines are heavily modified to produce optimum results on Hythane®. There are tradeoffs involved between emissions and performance. The fuel impacts are therefore difficult to isolate as different companies may have different philosophies with respect to optimization. Given the relatively early stage of development of this fuel it was difficult to determine the best modeling parameters.

There have not been any Hythane® powered vehicles offered for sale by Original Equipment Manufacturers. The Hythane® light duty vehicles that have been built have been modified by after market specialists. Given that a variety of engine operation strategies can be used, it is difficult to model a typical Hythane® vehicle. An engine that is operated at close to stoichiometric will have an efficiency and power output very close to the natural gas engine but will not get any of the NOx benefits available from a lean burn calibration. On the other hand a lean burn Hythane® engine will have very low NOx, a slight increase in thermal efficiency but a large drop in power and potentially a decrease in driveability. Some after market specialists have added a turbocharger or super charger to the Hythane® engine to recover some or all of the power lost from a lean burn calibration.

Cattelan and Wallace have published results for a production engine that was modified to operate on natural gas or Hythane® in a near stoichiometric condition. The Hythane® fuel contained 15% vol. hydrogen. The engine was tested on a dynamometer at three operating conditions approximating 0%, 15% and 30% of full load. The results of those tests are shown in the following table. The emissions are engine out results.

Table 5-1 Hythane® Results in Light Duty Application

	0% Load	15% Load	30% Load
Energy Consumption	Lower for Hythane	Same	same
NOx	Same	10-40% higher for Hythane	10-40% higher for Hythane
Total Hydrocarbons	10-20% lower for Hythane	Same	Same
Carbon Monoxide	10-20% lower for Hythane	Same	Same

If this engine was installed in a vehicle and the vehicle was tested over a driving cycle the energy consumption, hydrocarbon and carbon monoxide emissions would be the same as natural gas over the cycle. The nitrogen oxide emissions would be higher.

Hoekstra et. al. Published test results for a light duty engine operated on natural gas and natural gas with up to 50% vol. hydrogen. The engine was tested on a dynamometer at various loads and equivalence rations from 0.75 to 0.50, which is a very lean condition. They concluded that the addition of hydrogen generally increased the NOx levels for the same equivalence ratio but the hydrogen also significantly extended the lean limit of combustion so that lower equivalence ratios were possible and low levels of NOx were achievable at the very low equivalence ratios. They also found that the thermal efficiency was near the maximum achieved at the very low equivalence ratios.

Hoekstra also reported results from a single cylinder engine operated on natural gas, hydrogen and various blends of the two fuels. These results show the trade-offs inherent in engine calibration. On natural gas the higher the engine efficiency the higher the NOx. The maximum efficiency varied from 41% to 41.5% depending on the spark advance. On 100% hydrogen the peak efficiency varied from 41.5 to 42.5% again depending on the spark advance. For the blend of 30% hydrogen, the peak engine efficiency varied from 40.5 to 41.2%. The operating conditions had a lower equivalence ratio than when operated on natural gas.

For the light duty vehicles, GHGenius has been set so that the efficiency on Hythane® is the same as when the vehicle is operated on natural gas.

5.1.2 Hydrogen Internal Combustion Engine

GHGenius recognizes that most alternative fuel engines have not been developed to the same degree as gasoline powered engines and that there is potential to improve the efficiency of the engines over time. The model uses a single sided logistic function to describe this rate of improvement. The default values for the hydrogen internal combustion engines had been set the same as a natural gas engine at the low end but at the high end the efficiency of the engine is assumed to be 5% higher than the natural gas engine and 25% higher than the gasoline engine. For the year 2010 GHGenius projects a hydrogen engine has 1 percent better efficiency than a gasoline engine. The values for hydrogen were estimates and are not based on actual hydrogen engine performance since no original equipment manufacturers had built dedicated hydrogen engines at the time. The issue of the relative efficiency of hydrogen internal combustion engines has been reviewed for this work since it is fundamental to the issue.

Hydrogen has some unique combustion properties that provide both challenges and opportunities for its use in internal combustion engines. It has a high octane rating, which allows engines to have high compression ratios and increased efficiency. Hydrogen also has a higher specific heat ratio than gasoline, which leads to a higher ideal thermal efficiency of the engine. Hydrogen has a wide range of flammability limits which provides flexibility in the air to fuel ratio for the engine. One can find references in the literature (Barbir, Billings) to hydrogen engines being 20% more efficient than gasoline internal combustion engines. One can also find references to hydrogen engines having over a 50% thermal efficiency but this is the indicated peak efficiency and actual brake thermal efficiency is quite a bit lower, usually less than 40% (Stockhausen et al). The difference being engine mechanical and thermal losses.

There are also challenges with the use of hydrogen. It has a flame speed about an order of magnitude higher than gasoline at stoichiometric conditions, which is a factor in hydrogen's problem with premature ignition. While hydrogen has a high autoignition temperature it still limits the maximum compression ratio that can be achieved in the engine. At stoichiometric air fuel ratios NOx emissions from a hydrogen engine are very high. The preignition and NOx problems can be addressed by taking advantage of the wide flammability limits and operating the engine very lean (equivalence ratio of less than 0.5). The very lean operating conditions limits the power than can be developed by the engine and may result in unacceptable driveability in a vehicle.

Engine designers have to balance the positive and negative performance aspects of hydrogen when designing an engine that is suitable for a vehicle. Other factors will also become important such as manufacturing cost, reliability and maintenance costs. Ford has introduced two hydrogen powered passenger car prototypes in the past two years and Ballard had a hydrogen powered generator set that was developed by Ford and was briefly available. These engines can provide some guidance to how commercial hydrogen powered vehicles may be designed and perform.

The Ford P2000 hydrogen internal combustion engine powered vehicle was introduced in August 2001 and in the press release (Ford 2001) it was claimed that the engine's efficiency was improved by 25-30% over its gasoline counterpart. Similar claims of up to 25% better efficiency are made for the latest Ford hydrogen powered vehicle the Model U Concept (Ford, 2003). There were a number of SAE papers published by Ford staff that described the P2000 in much more detail than was described in the press releases and in these reviewed technical papers the engine efficiency values over the Federal Test procedure are substantially lower than stated in the press releases.

The P2000 vehicle is based on a 2.0 litre Ford Zetec engine. The compression ratio was increased to 14.5 and a number of other changes were made to the engine (Stockhausen, et al). There was a two phase development program for the engine. In Phase I the vehicle exhibited a 17.9% reduction in fuel economy over the city cycle, reasonable emissions but unacceptably poor acceleration performance. The highway driving fuel economy was not reported. In Phase II the equivalence ratio was increased from 0.55 to 0.7 under high load conditions. The acceleration improved (although not to the gasoline equivalent vehicle level), the NOx emissions increased and the fuel efficiency decreased. The city fuel economy was 14% better than the gasoline vehicle but the highway performance was only 6% better than the gasoline vehicle. At equal performance to the gasoline vehicle the city fuel economy performance was expected to be only 11% better than the gasoline and presumably the highway performance would decline as well. The combined fuel economy for equivalent performance is likely about 7% better than the gasoline vehicle.

The Model U employs a slightly different approach to the engine design where the compression ratio has been lowered to 12.2 to one and a supercharger has been added. No detailed information on fuel efficiency was found for this vehicle beyond the web site information.

One question that must be answered is that if hydrogen ICE vehicles are introduced commercially will they have similar specifications to these prototypes? The specifications may be different so that manufacturing costs could be lowered or reliability and durability improved. Original equipment natural gas vehicles are not optimized for natural gas. The compression ratios for these vehicles are generally the same or only marginally higher than the gasoline equivalent. The manufacturers have not been able to justify the engineering and development costs that would be associated with an optimized engine design with the relatively low demand for the vehicles. The same thing could happen with hydrogen vehicles.

The Ballard hydrogen fuelled electrical generating system that was briefly offered for sale in 2002 had the same basic engine as the natural gas version of the system. The compression ratio for both engines was 9.0 to one. The hydrogen engine produced about 16% less power and based on the fuel consumption quoted at maximum load had a brake thermal efficiency of 26.3% versus the 30.8% for the natural gas version. Ballard dropped this product from their product offering in part due to the higher than expected development costs for the natural gas version and without the natural gas version base the hydrogen engine could not support the total development costs.

The designers of a commercial hydrogen engine will have conflicting demands to meet. The technology and engineering groups will be driving towards higher efficiency to reduce fuel storage requirements and utilize the latest advances in technology. There probably is the potential to provide better performance than the P2000 achieved. On the other hand manufacturing will be trying to minimize the number of new parts in the engines and control the costs. It is not clear what marketing might require, emissions and fuel economy results or physical performance.

GHGenius does not generally use the best performance demonstrated for any technology but rather the performance that is likely to be demonstrated by the whole industry. Based on this philosophy and the above discussion, the relative fuel economy for a hydrogen internal combustion engine in the year 2010 in GHGenius has been increased to 1.05. This is slightly lower than that demonstrated in the P2000 prototype but in order to accomplish this the engine will still have to have a higher compression ratio than any vehicle offered by the manufacturers today. To be accepted in the marketplace it will be necessary to have the same or preferably better performance than the gasoline vehicles especially considering that there will be other limitations such as vehicle range that will be drawbacks to acceptance. The engine will have to be durable and reliable and due to the conservative nature of the auto manufacturers it is most likely that they will sacrifice some of the potential efficiency for a vehicle that performs well. The small reduction in assumed efficiency from the P2000 may not be enough to achieve the performance required but there is likely to be further gains in the understanding of how to optimize a hydrogen engine that could drive the efficiency higher.

The range of the hydrogen ICE vehicle has been set to be only 200 miles or one half of the gasoline version. The hydrogen vehicle still requires 7.25 kg of fuel to accomplish this. This quantity of fuel will be a challenge to package in the vehicle. The modelling assumptions for the hydrogen ICE vehicle are summarized in the following table.

Table 5-2 Hydrogen ICE Modelling Assumptions

	Hydrogen ICE
Relative Efficiency, City	1.08
Relative Efficiency, Highway	1.00
Relative Efficiency, Combined	1.05
Range, miles	200

5.2 FUEL CELLS

There are very few light duty fuel cell vehicles that have been built and very little data on their performance has been released. The relative efficiency factors in GHGenius have been developed based on reports in the literature. These factors and their development are described and the most recent data on fuel cell vehicle performance is compared to the 2010 projections.

5.2.1 Hydrogen 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 three 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 GHGenius is through to 2050 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.

GHGenius 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. The weight assumptions are shown in the following table.

Table 5-3 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

The most rigorous analyses that DTI have performed are 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 the following table. 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 5-4 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

GHGenius provides a relative efficiency of a hydrogen fuel cell vehicle in 2010 of 2.20, the same as shown above. It has not yet been possible to independently verify this value with data from the few prototype vehicles available.

The Honda FCV has been tested by the EPA and its fuel economy rating is not significantly different from the Honda Civic Hybrid. In GHGenius, the relative fuel economy factor for the FCV is much larger than that for a hybrid vehicle (2.2 vs. 1.5). The latest Ford Focus FCV has a relative fuel efficiency factor of 1.75 compared to a gasoline powered Focus according to data published by Ford. While this is better than the Honda the EPA or similar institution has not yet independently verified it.

There appear to be two reasons for the difference in performance of fuel cell vehicles compared to the GHGenius projections. The first is that the existing vehicles have a much higher incremental weight than is used in GHGenius and the second is that the vehicles are venting some hydrogen through the stack to maintain the proper environmental conditions in the stack during a shutdown.

The few vehicles that have been produced are much heavier than is modelled in GHGenius. The Ford Focus uses many weight saving material substitution techniques but still weighs about 800 pounds more than the gasoline Focus. They are still prototypes, which may not be benefiting from all of the weight reduction techniques that are available to mass production vehicles, but this is still and issue for FCV.

The issue of venting hydrogen is perhaps a more difficult technological challenge but one that will have to be overcome before the vehicles are commercialized. A recent issue of Science magazine (2003) described four environmental concerns that could arise from significant increases in anthropogenic hydrogen emissions. These included:

- Cooling of the lower stratosphere and disturbance of the ozone chemistry.
- Reduction in OH radical concentration in the troposphere with potential impacts on other trace gases such as methane and carbon monoxide,
- Increase in noctilucent clouds,
- Unforeseen effects on microbial communities.

More work is required on these issues before a complete understanding of the issues can be developed.

5.2.2 Vehicles with Onboard Reforming

Fuel cell vehicles that produce their hydrogen onboard from fuels such as methanol, ethanol, 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 fuelled 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. The 2010 value in GHGenius is 1.74.

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 and ethanol reforming as for gasoline. The value in GHGenius for 2010 is 1.43.

6. RESULTS

The GHG emission results are presented for 50 pathways and energy consumption data are presented for 36 pathways. It is not possible to present meaningful energy use for some of the electricity pathways. The emissions associated with the production of the vehicles have not been included in the results since GHGenius does not include these stages in the energy consumption and there is only very little difference between the different vehicle types.

There are five baseline pathways included for comparison purposes. These are gasoline powered internal combustion engines and a gasoline hybrid. Two diesel vehicles, the direct drive and a diesel hybrid. The fifth baseline vehicle is a natural gas vehicle. No hybrid using this fuel has been modelled.

There are 21 internal combustion engine pathways involving hydrogen that have been modelled. There are 25 fuel cell engine pathways, 21 of those involved hydrogen stored on board the vehicle and 4 use onboard reforming of a liquid fuel. The 50 pathways are identified in the following table. The hydrogen distribution distances have been kept the same but the feedstock transportation distances are different for some of the pathways because of the differences in location of the feedstocks.

Table 6-1 Description of Pathway Studied

Fuel Pathway	Engine	Comments
Gasoline	ICE	Baseline vehicle
Gasoline	ICE-Hybrid	Baseline vehicle
Diesel	ICE	Baseline vehicle
Diesel	ICE-Hybrid	Baseline vehicle
CNG	ICE	Baseline vehicle
Hythane (SMR)	ICE	20% hydrogen by volume
Coal to LH_2	FCV	Large central production with liquid hydrogen distribution
Coal to LH_2	ICE	Large central production with liquid hydrogen distribution
Coal to CH_2	FCV	Large central production with compressed hydrogen distribution
Coal to CH_2	ICE	Large central production with compressed hydrogen distribution
Wood to LH_2	FCV	Large central production with liquid hydrogen distribution
Wood to LH_2	ICE	Large central production with liquid hydrogen distribution
Wood to CH_2	FCV	Large central production with compressed hydrogen distribution
Wood to CH_2	ICE	Large central production with compressed hydrogen distribution
NG to LH_2	FCV	Large central production with liquid hydrogen distribution
NG to LH_2	ICE	Large central production with liquid hydrogen distribution
NG to CH_2	FCV	Large central production with compressed hydrogen distribution

NG to CH_2	ICE	Large central production with compressed hydrogen distribution
NG to CH_2, Onsite	FCV	Hydrogen produced onsite
NG to CH_2, Onsite	ICE	Hydrogen produced onsite
Thermonuclear to LH_2	FCV	Large central production with liquid hydrogen distribution
Thermonuclear to CH_2	FCV	Large central production with compressed hydrogen distribution
Thermonuclear to LH_2	ICE	Large central production with liquid hydrogen distribution
Thermonuclear to CH_2	ICE	Large central production with compressed hydrogen distribution
Electrolysis, Average Mix,	FCV	Hydrogen produced onsite
Electrolysis, Average Mix,	ICE	Hydrogen produced onsite
Electrolysis, Coal Powered,	FCV	Hydrogen produced onsite
Electrolysis, Coal Powered,	ICE	Hydrogen produced onsite
Electrolysis, Combine Cycle NG,	FCV	Hydrogen produced onsite
Electrolysis, Combine Cycle NG,	ICE	Hydrogen produced onsite
Electrolysis, Nuclear Power,	FCV	Hydrogen produced onsite
Electrolysis, Nuclear Power,	ICE	Hydrogen produced onsite
Electrolysis, Hydropower,	FCV	Hydrogen produced onsite
Electrolysis, Hydropower,	ICE	Hydrogen produced onsite
Methanol to Hydrogen,	FCV	Hydrogen produced onsite
Methanol to Hydrogen,	ICE	Hydrogen produced onsite
Ethanol to Hydrogen, (Wheat)	FCV	Hydrogen produced onsite
Ethanol to Hydrogen, (Wheat)	ICE	Hydrogen produced onsite
Ethanol to Hydrogen, (Straw)	FCV	Hydrogen produced onsite
Ethanol to Hydrogen, (Straw)	ICE	Hydrogen produced onsite
LPG to Hydrogen,	FCV	Hydrogen produced onsite
LPG to Hydrogen,	ICE	Hydrogen produced onsite
FT Distillate to Hydrogen,	FCV	Hydrogen produced onsite
FT Distillate to Hydrogen,	ICE	Hydrogen produced onsite
Gasoline to Hydrogen,	FCV	Hydrogen produced onsite
Gasoline to Hydrogen,	ICE	Hydrogen produced onsite
Methanol FCV	FCV	Hydrogen produced onboard
Ethanol FCV (straw)	FCV	Hydrogen produced onboard
Gasoline FCV	FCV	Hydrogen produced onboard
FT Distillate FCV	FCV	Hydrogen produced onboard

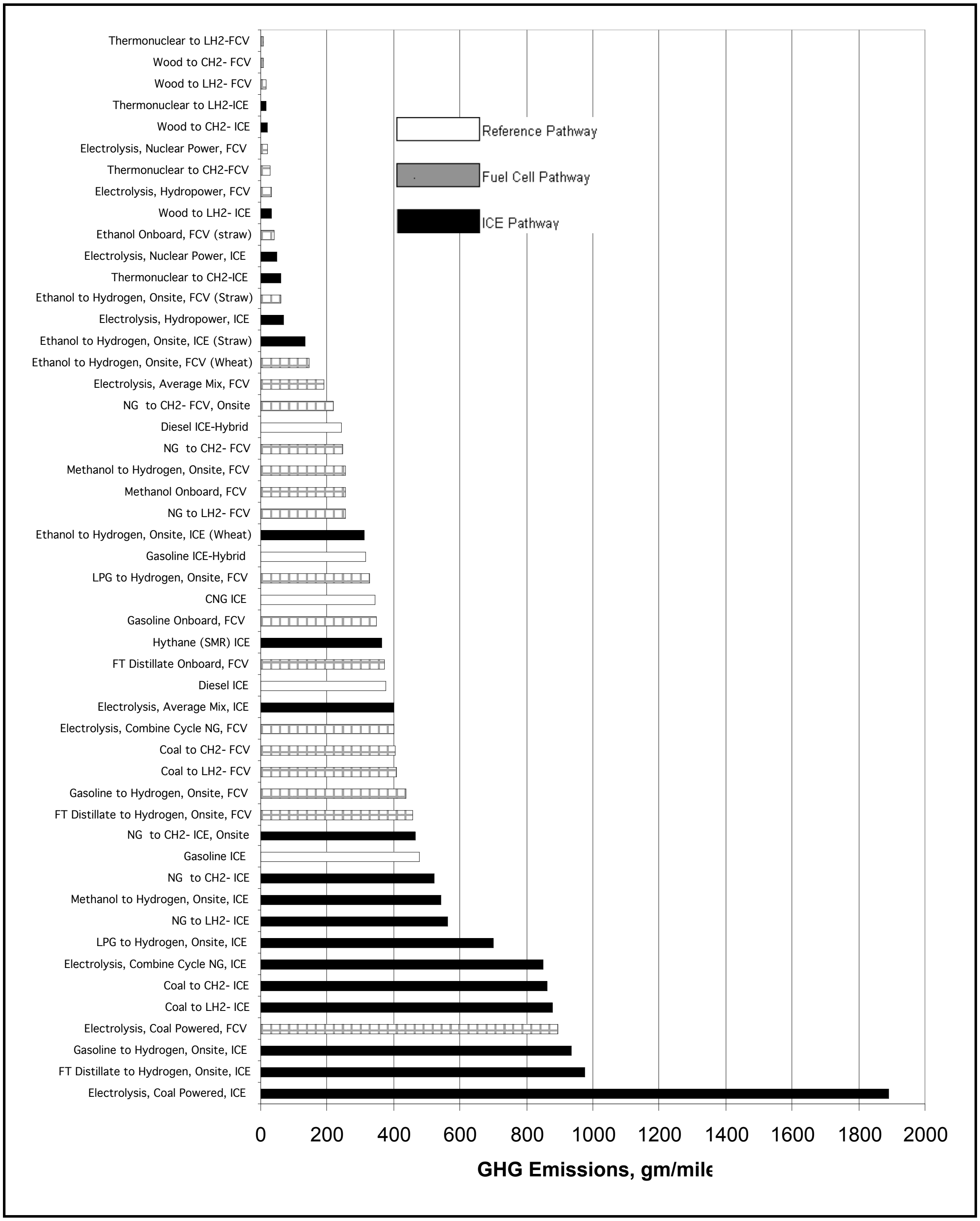
6.1 GREENHOUSE GAS EMISSIONS

The greenhouse gas emissions are presented as CO_2 equivalents including CO_2, methane and nitrous oxide. Methane emissions are weighted at 21 times their mass and nitrous oxide emissions at 310 times their mass (the IPCC weighting factors). GHGenius is run for the year 2010 since that is likely the earliest that these technologies may be available for commercial sale in significant quantities.

The relative performance of the 50 pathways with respect to their greenhouse gas emissions are shown in the following figure. The baseline vehicles, the hydrogen internal combustion vehicles and the fuel cell vehicles are shown with different shading. The values for each pathway are included in the Appendix.

There is a very wide range in the lifecycle emission performance of the 50 pathways studied. The emissions range from almost four times the emissions from the baseline gasoline powered vehicle to only 1.3% of the baseline gasoline vehicle. It is obvious that a “Hydrogen Economy” will have to be developed and implemented carefully to achieve the maximum possible environmental benefits. There are many pathways that will not provide the GHG emissions reductions necessary to meet Canada’s Kyoto Protocol obligations. Further discussion of the results is presented in the following section.

Figure 6-1 Relative GHG Emissions for 50 Pathways



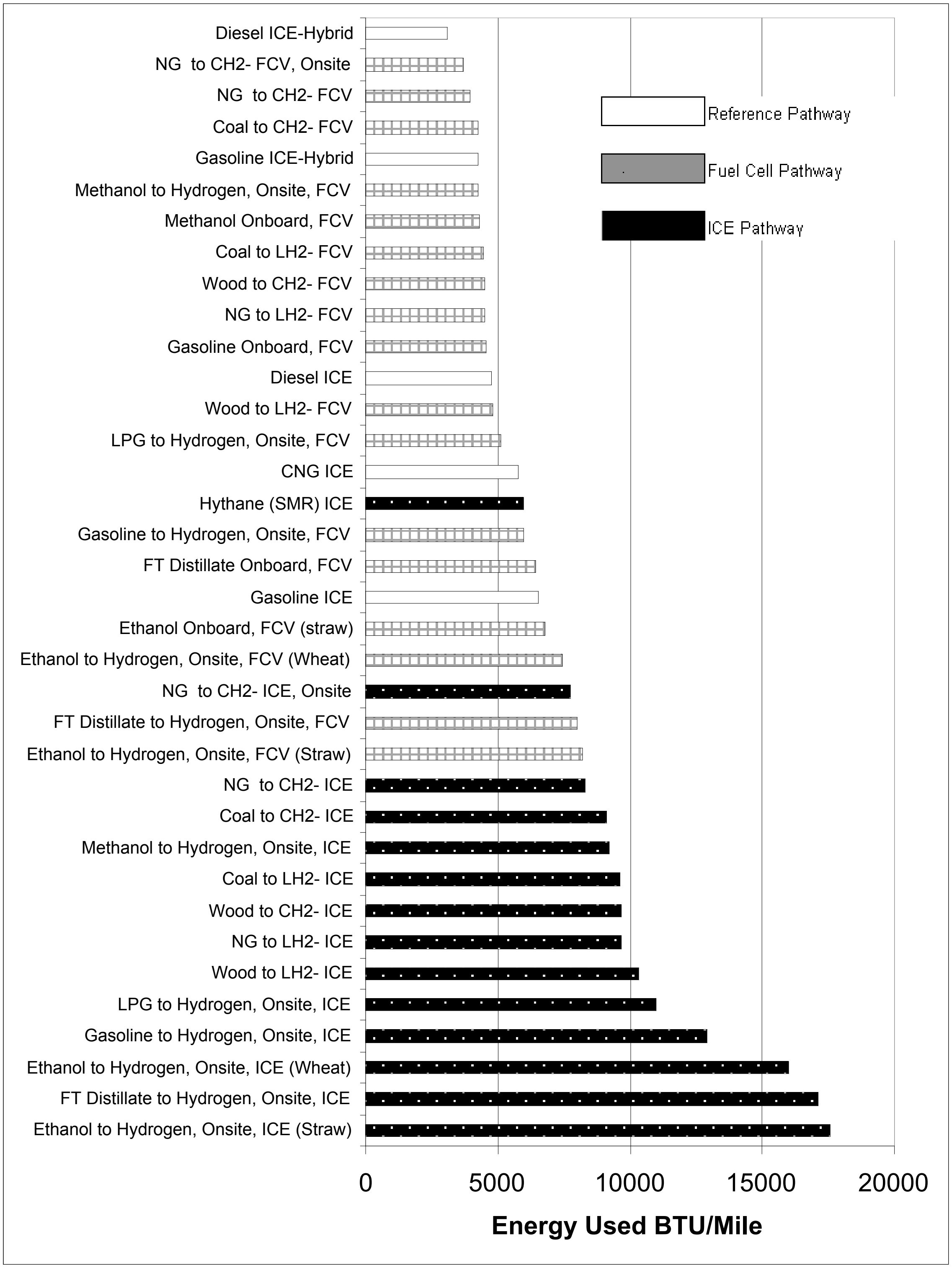
6.2 ENERGY CONSUMPTION

The results for the lifecycle energy consumption are shown in the following figure. The values for the pathways are found in the Appendix. The order of the results is quite different from the order of the greenhouse gas emission results because the biomass feedstocks, which don't contribute to GHG emissions, but do contain energy and some of the biomass pathways consume significant amounts of energy in their transformation.

The most energy efficient pathway is the diesel hybrid. The combination of the high efficiency engine combined with the hybrid drive train using a fuel with little conversion energy used in processing yields the lowest lifecycle energy use. This pathway is not currently available commercially and one of the primary challenges for the pathway is meeting the 2004 to 2007 criteria contaminant emission standards.

There is more stratification between fuel cell vehicles and internal combustion engine vehicles with the energy consumption set on pathways than in the larger set looking at GHG emissions. The best hydrogen ICE consumes more energy than the gasoline baseline vehicle. The direct hydrogen pathways have better efficiency than the pathways that involve an energy carrier. All but four of the fuel cell pathways are better than the gasoline baseline vehicle. The four exceptions are all indirect pathways. Further discussion on the energy results is presented in the next section.

Figure 6-2 Relative Energy Consumption Results for 36 Pathways



7. DISCUSSION AND CONCLUSIONS

GHG emissions for the hydrogen pathways range from 1.3% to 395% of the emissions of the gasoline baseline vehicle. With such a wide range in the GHG emission and energy use results it is clear that an unmanaged “Hydrogen Economy” is not a panacea for solving the GHG emissions problem or for resolving the energy security issues for energy importing nations. There are hydrogen pathways that can produce very significant GHG emission reductions and energy savings but there are also pathways that would result in increased GHG emissions and increased energy use. One of the challenges of managing a transition to a hydrogen economy will therefore be ensuring that society does receive the maximum possible benefits.

All but one of the fuel cell pathways (electrolysis from coal power) has GHG emissions better than the gasoline baseline vehicle. For the same hydrogen source the GHG emissions for the fuel cell vehicle are about one half of those for the hydrogen internal combustion engine. There are some hydrogen ICE pathways that have lower GHG emissions than a gasoline hybrid vehicle but the fuel pathways are either still under development or there are resource issues with the pathway that are discussed below.

7.1 FUEL CELLS VS. HYDROGEN INTERNAL COMBUSTION ENGINES

Given the relatively small amount of data available on the performance of the hydrogen internal combustion engine and the fuel cell vehicles it is appropriate to consider how more efficient hydrogen internal combustion engines or less efficient fuel cell vehicles may impact the results.

The efficiency of the hydrogen ICE vehicle that has been modelled is based on the published results of an early prototype from an original equipment manufacturer. There are many references in the literature that suggest that the efficiency can be higher but these references generally do not consider the other important issues such vehicle performance, manufacturing cost and maintenance issues. The compromises required to meet these other important criteria generally result in lower engine efficiency.

It could be argued that with increased development resources and the potential for a large market the hydrogen internal combustion engine could be made more efficient than has been modelled here. To test the impact of this it has been assumed that instead of the demonstrated 7% improvement in fuel economy the vehicles are capable of achieving a 20% improvement over the combined city and highway cycles (the press releases say up to 25% but that presumably is for the city portion only).

This change to a higher efficiency would move only two of the pathways that are currently higher GHG emitters than the baseline gasoline engine, the methanol to hydrogen and the central SMR plant with compressed hydrogen delivery, to being lower emitters than the baseline gasoline. There would still be eight ICE hydrogen pathways that are higher emitters than the gasoline baseline.

The best of the “commercial” hydrogen pathways, the onsite SMR system would produce GHG reductions of 15% compared to the gasoline vehicle. The emissions would not be as low as the GHG emissions from the CNG vehicle, the diesel vehicle or the gasoline hybrid vehicle.

The existence of higher efficiency internal combustion engines will not significantly change the conclusion that only a few hydrogen pathways coupled with an internal combustion engines are capable of producing large GHG emissions benefits. There is more discussion of these pathways in a later section.

There is a considerable gap between the 2.2 times better efficiency for the fuel cell vehicles in GHGenius and the 1.5 times factor demonstrated for the Honda FCV. A portion of this is the extra weight of the prototype vehicles and a portion is the use of hydrogen to maintain the proper environment in the fuel cell during shutdown. There should be improvements in both of these areas as the vehicle move closer to commercialization. If the fuel cell vehicles can only achieve 1.8 times better fuel efficiency (Ford claim the latest Focus is at 1.75 times better efficiency) then the GHG emissions for all of the fuel cell vehicle pathways will increase. The pathways that produce hydrogen from gasoline onsite, from coal and from electricity produced by combined cycle natural gas all rise to higher GHG emissions than the baseline gasoline vehicle.

The pathways that use SMR and methanol to hydrogen would have GHG benefits of about 35% instead of about 45% with the lower efficiency of the FCV. This puts them about equal to the gasoline hybrid vehicles modelled here.

The same different assumptions for hydrogen ICE efficiency and fuel cell vehicle efficiency are considered for their impacts on the lifecycle energy use.

The energy used for the hydrogen ICE vehicles is all higher than the gasoline baseline vehicle in the base case. Increasing the efficiency of the hydrogen engine does not change this. The best hydrogen pathway, the onsite SMR system is still 4% above the baseline gasoline vehicle.

If the lower efficiency of the FCV is modelled the two best pathways become the diesel and gasoline hybrid vehicles. There is still a cluster of fuel cell pathways that use natural gas, methanol, coal and wood that have lower energy use than the gasoline baseline vehicles. Most of these pathways would be less energy efficient than the non-hybrid diesel vehicle however.

The combination of higher efficiency internal combustion engines and lower efficiency fuel cell vehicles would still result in the emissions for the FCV being two thirds of the emissions of the hydrogen internal combustion engine. Given the state of development of the two technologies and the challenges that each face in obtaining their maximum efficiency it is considered unlikely that that this scenario of progress with the hydrogen ICE and no progress with the FCV would materialize.

7.2 COMMERCIAL VS. DEVELOPING HYDROGEN PATHWAYS

There are 14 pathways with GHG emissions of less than 20% of the baseline gasoline vehicle. These pathways have very low emissions on both FC and ICE vehicles but most of them are for technologies that have not yet been demonstrated on a commercial scale. Of the top 14 pathways only hydrogen from electrolysis from nuclear power or hydroelectricity could be considered commercial hydrogen production pathways. While there is some potential to increase hydroelectricity in Canada there is not enough potential to supply all transportation needs. Nuclear power could be expanded if the public acceptance issues could be overcome. There are other issues with the electricity pathways that are discussed in the next section.

The pathways that produce some of the largest GHG reductions but are under development and are not commercial include the Thermonuclear cracking water, and the wood or biomass gasification to produce hydrogen. The Thermonuclear option is under investigation in the US but it is not expected to be developed until after 2030. It involves both a new generation of nuclear reactor and a new process to produce hydrogen at very high temperatures.

The gasification of wood is a process that is receiving quite a bit of attention from researchers around the world. Small demonstration facilities have been operated but further development of the gasification technology is required to increase the operating temperatures and to improve the gas cleanup steps that are used prior to concentrating and purifying the hydrogen. The gasification technology can also be used to produce other transportation fuels including methanol, ethanol, mixed alcohols and FT distillates. In Canada there were significant resources applied to biomass gasification processes in the late 1970's and early 1980's without commercial success. Little effort has been expended in Canada recently but there has been continued development of the technology in the United States and Europe.

There is interest in Canada and other parts of the world in using managed forests to sequester carbon through the use of fast growing species. This can provide a temporary increase in the amount of carbon stored in plant biomass but eventually the biomass must be utilized otherwise it will slowly decompose and put the carbon back into the atmosphere. The development of wood gasification systems to produce hydrogen may be a method of producing transportation fuel from these managed forests.

It could be argued that there are three commercial hydrogen pathways, electrolysis, steam methane reforming and methanol decomposition to hydrogen There are commercial applications of LPG and naphtha reforming but for commercial and technical reasons these pathways are not likely to be widely commercialized.

Hythane® offers no GHG or energy benefit over natural gas when the hydrogen is produced from natural gas. Hythane's only role in the transition to a "Hydrogen Economy" would be to build a load prior to the implementation of hydrogen consuming engines. This role is likely to be limited as most hydrogen production systems have limited turn down capability and when they are appropriately sized for the hydrogen requirements of a Hythane® system are likely to be too small for a pure hydrogen load.

7.3 Low GHG Electricity

The GHG emissions from electrolysis vary significantly depending on the energy source used to produce the hydrogen. Electricity from a coal-fired power plant leads to increases in GHG emissions when used in either fuel cells or internal combustion engines. When the electricity is produced in a combined cycle natural gas fired power plant there is a small reduction in GHG emissions when the hydrogen is used in fuel cell vehicles but an increase when the hydrogen is used in internal combustion engines. In most regions of Canada one of these two electricity generating systems is used as the incremental source of electricity.

The GHG emissions from electrolytic hydrogen are very low when the electricity is produced from nuclear power plants or hydroelectric facilities. These two sources of electricity account for about 80% of the electricity generated in Canada today. There is some potential to expand the hydroelectric generation potential in Canada with untapped resources in British Columbia, Manitoba, Quebec and Newfoundland but most of the expansion opportunities are only at the feasibility stage and may never be built. There have not been any new nuclear generation capacity added to the system in Canada for many years. Existing plants are nearing the end of their licensed life and it is not clear how many of them will be refurbished. There are no active plans to build new facilities in Canada and it is not clear how the public would react to new nuclear facilities.

Electricity produced from wind resources or small run of the river hydroelectric facilities would have very low GHG emissions similar to the emissions calculated from hydropower in the model. Hydrogen produced from this electricity would have very low emissions whether it was used in a fuel cell vehicle or an internal combustion engine. The GHG emissions benefit from hydrogen produced by electrolysis using these sources of electricity is less than the GHG emission reductions that would occur if this electricity were to displace electricity produced by a coal powered facility.

One megawatt-hour of electricity from a coal-fired power plant produces 1.08 million grams of CO_2eq emissions (1.08 tonnes). This same amount of electricity would produce 20.3 kg of hydrogen. If this amount of hydrogen were used in a hydrogen ICE vehicle it would drive the car 596 miles and it would displace the 272,350 grams of CO_2eq emissions that would be produced driving the vehicle on gasoline. Using the hydrogen in a fuel cell vehicle would propel the vehicle 1187 miles and would avoid 569,150 grams CO_2eq emissions from a gasoline engine. Thus using the low GHG electricity to displace gasoline will only provide 25 to 50% of the benefit that could be derived if the electricity was used to displace coal-fired power. This would be a wasteful use of the resource.

7.4 OTHER COMMERCIALIZATION ISSUES

There are other issues besides GHG emissions and energy consumption that will influence which of the hydrogen pathways would be adopted if the “Hydrogen Economy” were to expand. The costs of hydrogen produced by each of the pathways is one obvious influencing factor. The ease of operation of the various hydrogen production systems will also greatly influence which of the hydrogen pathways gets adopted.

While it is beyond the scope of this work to examine the costs of hydrogen from each of the pathways the energy consumption data could be considered a rough proxy for the fuel costs per mile travelled. Since many of the forms of energy can be substituted for each other there is an approximate correlation between the energy consumed and the cost. This is not perfect since the substitution of one form of energy for another is not perfect but it can provide some guidance. Based on the energy results the use of hydrogen in an ICE is likely to be more costly than the use of gasoline even before the extra hydrogen specific cost issues are considered. Even the best hydrogen pathway is less energy efficient than a diesel hybrid and thus is likely to be more expensive. Again this is before any hydrogen specific cost issues are addressed.

When the relative rankings from the energy results and the GHG emission results are considered together it is noted that the coal to hydrogen pathways have some of the best energy efficiency results but the highest GHG results. This would suggest that coal may be one of the lowest cost methods of producing hydrogen but this pathway will produce only minimal GHG reductions when used in fuel cell vehicles and increases in GHG emissions if the hydrogen is used in internal combustion engines.

Hydrogen systems for transportation applications will have to be easy to operate, respond quickly to varying loads and be capable of starting up and shutting down with minimal attention. Of the commercial pathways electrolysis systems are the easiest to operate, followed by the methanol to hydrogen systems and then the steam methane reformers. The steam methane reformers often have a lifetime measured in terms of system start-ups. If these systems are applied to applications that required starting and stopping the systems are often idled rather than shutting them down cold. This idling will have a detrimental impact on the GHG emission performance modelled here and the energy consumption.

7.5 Conclusions

Not all of the hydrogen pathways investigated will produce GHG benefits and reduced energy consumption. The "Hydrogen Economy" must therefore be implemented carefully if it is to provide benefits to society.

Hydrogen pathways are more likely to provide benefits if fuel cells are used to convert the hydrogen to useful work rather than using an internal combustion engine. The benefits arise from the higher efficiency of the fuel cell compared to the hydrogen internal combustion engine. It is forecast that the fuel cell will be more than twice as efficient as the hydrogen internal combustion engine in transportation applications. Even if there are breakthroughs with the internal combustion engine and no further development of the fuel cell the fuel cell will still be 50% more efficient than the ICE.

Many of the hydrogen pathways that produce the lowest greenhouse gas emissions and thus could be used in either the fuel cell or the internal combustion engine are at the early stage of development and are not yet commercial pathways. The exceptions would be hydrogen produced by electrolysis when the electricity is produced by a low carbon intensity pathway such as nuclear power, hydropower, or wind energy. There are supply limitations (either technical or social) to most of these pathways. The use of this hydrogen produces very low emissions from both fuel cell vehicles and ICE vehicles but even greater GHG emissions reductions could be achieved if this electricity was used to displace coal fired electricity instead of producing hydrogen.

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9. APPENDIX

Table 9-1 GHG Emissions Values

Pathway	GHG emissions Grams/Mile
Electrolysis, Coal Powered, ICE	1,892.7
FT Distillate to Hydrogen, Onsite, ICE	974.8
Gasoline to Hydrogen, Onsite, ICE	937.1
Electrolysis, Coal Powered, FCV	896.5
Coal to LH_2- ICE	877.8
Coal to CH_2- ICE	863.8
Electrolysis, Combine Cycle NG, ICE	851.1
LPG to Hydrogen, Onsite, ICE	700.8
NG to LH_2- ICE	561.4
Methanol to Hydrogen, Onsite, ICE	541.6
NG to CH_2- ICE	520.7
Gasoline ICE	479.5
NG to CH_2- ICE, Onsite	466.3
FT Distillate to Hydrogen, Onsite, FCV	456.4
Gasoline to Hydrogen, Onsite, FCV	438.7
Coal to LH_2- FCV	410.9
Coal to CH_2- FCV	404.3
Electrolysis, Combine Cycle NG, FCV	402.0
Electrolysis, Average Mix, ICE	401.2
Diesel ICE	374.6
FT Distillate Onboard, FCV	373.9
Hythane (SMR) ICE	364.2
Gasoline Onboard, FCV	347.1
CNG ICE	346.0
LPG to Hydrogen, Onsite, FCV	327.8
Gasoline ICE-Hybrid	314.3
Ethanol to Hydrogen, Onsite, ICE (Wheat)	312.3
NG to LH_2- FCV	255.9
Methanol Onboard, FCV	254.6
Methanol to Hydrogen, Onsite, FCV	253.1
NG to CH_2- FCV	245.2
Diesel ICE-Hybrid	243.0
NG to CH_2- FCV, Onsite	219.3
Electrolysis, Average Mix, FCV	188.5
Ethanol to Hydrogen, Onsite, FCV (Wheat)	145.5
Ethanol to Hydrogen, Onsite, ICE (Straw)	133.3
Electrolysis, Hydropower, ICE	68.4
Ethanol to Hydrogen, Onsite, FCV (Straw)	61.5
Thermonuclear to CH_2-ICE	60.4
Electrolysis, Nuclear Power, ICE	48.2
Ethanol Onboard, FCV (straw)	39.2
Wood to LH_2- ICE	33.1
Electrolysis, Hydropower, FCV	30.5
Thermonuclear to CH_2-FCV	27.3
Electrolysis, Nuclear Power, FCV	20.9

Wood to CH_2- ICE	18.8
Thermonuclear to LH_2-ICE	15.6
Wood to LH_2- FCV	14.5
Wood to CH_2- FCV	7.8
Thermonuclear to LH_2-FCV	6.3

Table 9-2 Energy Consumption

Pathway	BTU/Mile
Ethanol to Hydrogen, Onsite, ICE (Straw)	17,573
FT Distillate to Hydrogen, Onsite, ICE	17,115
Ethanol to Hydrogen, Onsite, ICE (Wheat)	15,979
Gasoline to Hydrogen, Onsite, ICE	12,887
LPG to Hydrogen, Onsite, ICE	10,985
Wood to LH_2- ICE	10,326
NG to LH_2- ICE	9,674
Wood to CH_2- ICE	9,674
Coal to LH_2- ICE	9,629
Methanol to Hydrogen, Onsite, ICE	9,220
Coal to CH_2- ICE	9,139
NG to CH_2- ICE	8,329
Ethanol to Hydrogen, Onsite, FCV (Straw)	8,197
FT Distillate to Hydrogen, Onsite, FCV	7,982
NG to CH_2- ICE, Onsite	7,761
Ethanol to Hydrogen, Onsite, FCV (Wheat)	7,449
Ethanol Onboard, FCV (straw)	6,803
Gasoline ICE	6,540
FT Distillate Onboard, FCV	6,416
Gasoline to Hydrogen, Onsite, FCV	5,998
Hythane (SMR) ICE	5,962
CNG ICE	5,765
LPG to Hydrogen, Onsite, FCV	5,105
Wood to LH_2- FCV	4,796
Diesel ICE	4,738
Gasoline Onboard, FCV	4,580
NG to LH_2- FCV	4,490
Wood to CH_2- FCV	4,490
Coal to LH_2- FCV	4,469
Methanol Onboard, FCV	4,307
Methanol to Hydrogen, Onsite, FCV	4,277
Gasoline ICE-Hybrid	4,268
Coal to CH_2- FCV	4,239
NG to CH_2- FCV	3,954
NG to CH_2- FCV, Onsite	3,685
Diesel ICE-Hybrid	3,091