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Life cycle analysis of vehicles powered by a fuel cell and by internal combustion engine for Canada

Nada Zamel, Xianguo Li *

Department of Mechanical Engineering, University of Waterloo, Waterloo, Ont., Canada N2L 3G1

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Abstract

The transportation sector is responsible for a great percentage of the greenhouse gas emissions as well as the energy consumption in the world. Canada is the second major emitter of carbon dioxide in the world. The need for alternative fuels, other than petroleum, and the need to reduce energy consumption and greenhouse gases emissions are the main reasons behind this study. In this study, a full life cycle analysis of an internal combustion engine vehicle (ICEV) and a fuel cell vehicle (FCV) has been carried out. The impact of the material and fuel used in the vehicle on energy consumption and carbon dioxide emissions is analyzed for Canada. The data collected from the literature shows that the energy consumption for the production of 1 kg of aluminum is five times higher than that of 1 kg of steel, although higher aluminum content makes vehicles lightweight and more energy efficient during the vehicle use stage. Greenhouse gas regulated emissions and energy use in transportation (GREET) software has been used to analyze the fuel life cycle. The life cycle of the fuel consists of obtaining the raw material, extracting the fuel from the raw material, transporting, and storing the fuel as well as using the fuel in the vehicle. Four different methods of obtaining hydrogen were analyzed; using coal and nuclear power to produce electricity and extraction of hydrogen through electrolysis and via steam reforming of natural gas in a natural gas plant and in a hydrogen refueling station. It is found that the use of coal to obtain hydrogen generates the highest emissions and consumes the highest energy. Comparing the overall life cycle of an ICEV and a FCV, the total emissions of an FCV are 49% lower than an ICEV and the energy consumption of FCV is 87% lower than that of ICEV. Further, CO_2 emissions during the hydrogen fuel production in a central plant can be easily captured and sequestrated. The comparison carried out in this study between FCV and ICEV is extended to the use of recycled material. It is found that using 100% recycled material can reduce energy consumption by 45% and carbon dioxide emissions by 42%, mainly due to the reduced use of electricity during the manufacturing of the material.
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Keywords: Fuel cell vehicle; Internal combustion engine vehicle; Life cycle analysis; Greenhouse gas emissions; Energy efficiency

1. Introduction

Global warming, greenhouse gas emissions, and the quality of the air have all been a major concern. It is important to identify the major contributors to greenhouse gas (GHG) emissions in order to develop effective methods and strategies for their reduction.

According to the Canadian Statistics, Canada contributes about 2% of global GHG, which makes it the second major contributor of GHG in the world on a per capita basis. One of the major contributors to the emission of greenhouse gases, such as carbon dioxide, and methane, is the use of automobiles and the burning of fuel (gasoline and diesel). In the year 2002, the transportation sector in Canada was responsible for 160 Mt (million ton) of carbon dioxide (34% of total emissions by all sectors) and 2000 PJ of energy consumption (28% of total energy consumption by all sectors) [1].

These statistics raise a very important issue that drives research efforts to find a suitable replacement to the internal combustion engine (ICE) that is currently found in almost every automobile driven on the roads and highways. Internal combustion engines burn the fuel inside the engine. The combustion of the fuel, such as gasoline or diesel, pro-

* Corresponding author. Tel.: +1 519 888 4567; fax: +1 519 885 5862.
E-mail address: X6li@uwaterloo.ca (X. Li).

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duces carbon dioxide that is emitted in to the air through the exhaust. In order to reduce the emission of greenhouse gases produced by vehicles, it is necessary to find suitable alternatives. One of the most promising technologies that are in the research and development stage is the fuel cell. Fuel cells use hydrogen and oxygen in order to produce electricity. The byproducts of this reaction are heat and water.

There are many literature studies concerning future technologies and different stages of the life cycle, often with different results and conclusions, depending on the assumptions made and the economic reality of the country concerned. Borgan and Venkateswaran [2] estimated fuel cycle energy use and CO_2 emissions of various transportation technologies. Their study included EVs, hybrid electric vehicles (HEVs), FCVs, and ICEVs powered with different fuels, for a total of 19 propulsion system/fuel options. Their analysis was conducted for typical mid-size passenger cars to be introduced in 2001. The conclusion of this study was that ICEVs fueled with gasoline, methanol, CNG, and ethanol had higher primary energy consumption rates than electric propulsion technologies (i.e., EVs, HEVs, and FCVs). Ethanol vehicles were shown to have the lowest CO_2 emission rate. The study revealed that on the basis of the average electric generation mix in the United States, EVs, and HEVs generated fewer CO_2 emissions than gasoline ICEVs [3].

Delucchi [4] estimated fuel cycle emissions of GHGs for various transportation fuels and for electricity generation. In addition, the study included the emission and energy use involved in the manufacture of motor vehicles, maintenance of transportation systems, manufacture of materials used in major energy facilities, and changes in land use caused by the production of biofuels. The study concluded that coal based fuels generally increase GHG emission. Slight to moderate reductions in GHG emissions result from using NG-based fuels. Use of solar energy via electricity or hydrogen nearly eliminates GHG emissions. Finally, the use of nuclear energy via electricity or hydrogen greatly reduces GHG emissions [3].

Weiss et al. [5] assessed the technologies for new passenger cars that will be developed and commercialized by the year 2020. It was reported that their quantitative results are subject to the uncertainties due to projections into the future and those uncertainties are larger for rapidly developing technologies such as fuel cells and new batteries. A more recent study by Rousseau and Sharer [6] analyzes and compares ICEV and FCV from by a well-to-wheel perspective using GCtool, PSAT, and GREET (computer software used to analyze the life cycle of vehicles). The main conclusion of the study was that hybrid electric vehicles are competitive in terms of the total energy cycle when hydrogen is produced by natural gas reforming. They suggest that one of the major issues with fuel cells is hydrogen production and so an intermediate step toward the hydrogen economy could involve using hydrogen ICEs to allow the development of the upstream side of the technologies.

Recently, a negative attitude/opinion towards hydrogen economy and fuel cell technology in vehicles has surfaced in the United States. Wald [7] in an article published in Scientific American discusses the negative aspects of fuel cell technologies in vehicles without showing the details behind the various analyses and results, and focuses mostly on the obstacles surrounding fuel cell commercialization, such us the infrastructure, transportation, and cost. His main conclusion calls for diverting research attention to other sources such as solar and wind power. Kreith and West [8] presented a critical cradle to grave analysis of all the major pathways to produce hydrogen and to utilize it as an energy carrier to generate heat or electricity, and argued strongly against the concept of hydrogen economy and fuel cell vehicles.

All the above literature studies are almost invariably based on the economic and energy realities in the United States. The present study documents the various assumptions and simplifications made in the full life cycle analysis, and presents the facts and proper results from which proper conclusions are drawn from a neutral standpoint without pre-conceived notion for and against hydrogen fuel cell vehicles. The objective of this study is to conduct a life cycle analysis of fuel cell vehicles (FCV) and internal combustion engine vehicles (ICEV) which includes not only operation of the vehicle on the road but also the manufacture and distribution of both the vehicle and the fuel during the vehicle's entire lifetime (cradle to grave analysis). In addition, the use of recycling in the manufacture of the vehicle will also be considered. ICEV is considered fuelled by gasoline, while FCV is fuelled by hydrogen. Four different methods of hydrogen production will be assessed, including using coal and nuclear power to produce electricity first and then extract hydrogen through electrolysis and via steam reforming of natural gas in a natural gas plant and in a hydrogen refueling station. The study has been conducted based on the economic and energy realities in Canada. Canadian statistics are taken into consideration. Also, the Canadian electricity mix is considered in the analysis for the materials production, vehicle manufacturing, and fuel distribution, etc.

2. Methodology

The life cycle of automobile technology includes all the major steps required to make up the life cycle of that system. Two major cycles make up the total life cycle of the automobile; the "vehicle cycle" and the "fuel cycle". The "vehicle cycle" follows the sequences below [9]:

- *Vehicle material production*: Energy use and greenhouse gas emissions from vehicle materials production are counted in this stage. In ICE vehicles and fuel cell vehicles, the steel used to produce the vehicle is counted for. In addition to the steel, the materials needed to produce the fuel cell such as polymer membrane, platinum as catalyst, graphite, etc., are also considered in this part of the analysis.

- *Vehicle assembly*: The energy required and greenhouse gas emissions for transport of vehicles during assembly are quantified here. Because of the complex supply chain in the automobile industry and the associated difficulty in estimating vehicle assembly energy requirements, assembly energy is typically estimated as a linear function of vehicle mass.
- *Vehicle distribution*: The energy needed and greenhouse gas emissions during the transport of a vehicle from the assembly line to the dealership are counted in this stage.
- *Vehicle maintenance*: It includes energy consumption and greenhouse gas emissions during maintenance and repair over the lifetime which is assumed to be 300,000 km.
- *Vehicle disposal* (*recycling*): After a vehicle's life, the automobile is shredded. The disposal energy is the sum of energy needed to move the bulk from the dismantler to a shredder and the shredding energy.

While, the "fuel cycle" follows the sequences described below [9]:

- *Feedstock production*: Energy consumption and greenhouse gas emissions during the production of the raw materials in order to obtain the fuel needed (either hydrogen or gasoline).
- *Feedstock transport*: The raw material for gasoline and hydrogen has to be transported to the refineries and reforming plants. Energy consumption and greenhouse gas emissions during the transport of raw materials are counted in this stage.
- *Fuel production*: Energy consumption and greenhouse gas emissions during refining of the raw materials.
- *Fuel distribution*: Distribution of the gasoline and hydrogen. Detailed discussion is to follow in later sections.
- *Fuel use*: It is during the vehicle use. It includes energy consumption (fuel) and greenhouse gas emissions during the consumption (burning) of fuel.

This study is different from the other studies in that the fuel use is analyzed in the "fuel cycle" rather than the "vehicle cycle". This is so since greenhouse gases regulated emissions and energy use in transportation (GREET) is used to analyze the "fuel cycle". The software is designed to calculate the energy consumption and emissions associated with the fuel use. GREET is a software developed and made available by Argonne National Laboratories. The software is available from their website. GREET 1.6 was used to carry on the analysis of the "fuel cycle" [3].

The analysis of energy consumption and GHG emissions associated with the vehicle life cycle has been carried out using published literature. Two main literature sources have been used to obtain the data used to analyze the "vehicle cycle" [5,10]. The data necessary to analyze the "vehicle cycle" is the weight of the vehicle, the distribution of the material used in the vehicle by weight and the energy consumption and GHG emissions associated with each step in the "vehicle cycle". The analysis of all the phases of both cycles has then been combined to create the total life cycle analysis of the automobile.

The effect of the use of recycled material in the manufacturing of the automobile has been also addressed. In addition, the analysis has been extended to estimate the energy consumption and GHG emissions in future vehicles. Finally, the overall (well-to-wheel) efficiency of the life cycle of ICEV and FCV is compared.

3. Scope

The methodology described above is used to characterize the following fuel and vehicle technologies.

Fuels:

- hydrogen from natural gas (NG) reforming and distributed to refueling stations via pipelines from a central plant;
- use of electrolysis via coal to extract hydrogen;
- use of electrolysis via nuclear energy to extract hydrogen;
- hydrogen from natural gas reforming in hydrogen refueling stations;
- gasoline from crude oil.

Vehicle technologies:

- PEM fuel cell automobile (with present and future estimated vehicle weight) utilizing hydrogen as fuel;
- spark ignition internal combustion engine automobile (with present and future estimated vehicle weight) utilizing gasoline as fuel.

4. Limitations

The analysis discussed in this paper is based on published data from literature and on GREET and like any other analysis has some limitations, as stated below:

- The boundaries of the physical system are such that secondary energy and environmental effects are not quantified. For example, energy consumption and emissions during the operation of a steam reforming plant of natural gas are quantified, but the energy and emissions involved in making the steel, concrete or other materials embodied in the plant structure or for the construction of the plant itself are not counted.
- Data used for the analysis is for mid-size family passenger vehicles (average weight of the vehicle is 1300 kg).
- GREET, just like any other software, has many built in assumptions and equations.

5. Analysis

The analysis carried out using GREET relies on many inputs to the software. The GREET model calculates the energy use and emission rates of various combinations of vehicle technologies and fuels on a per-mile basis. This analysis estimates the life of the vehicle to be 300,000 km (186,411 mile). Therefore, the output that was obtained from GREET was multiplied by the average life in miles to obtain the total energy consumption and GHG emissions. The GREET model relies on the efficiency of each step in obtaining and refining the fuel in order to calculate the energy consumption. The carbon dioxide emissions associated with the obtaining and refining of the fuel, are calculated based on the methods used. For example, if hydrogen obtained via NG in a NG power plant is the fuel being analyzed, the user must decide on the following inputs: power plant with steam, transportation of hydrogen and NG (distance and method and efficiency), electricity mix used and its efficiency. GREET follows a built in table with emission factors for each step. In addition, GREET relies on the lower heating values of the fuel in its calculation. Built in tables with the fuel properties are found in GREET. These tables can be modified but for the purpose of this study the default inputs were used. The fuel use emissions are obtained from the carbon content in the fuel.

This analysis uses the Canadian electricity mix, as shown in Table 1. As it can be seen from this table, natural gas is the biggest contributor to the Canadian electricity mix. Coal is also used but in lower quantities. The electricity mix in Canada shown in Table 1 is different from a single year statistics of electricity production in Canada, for example, for year 2002 [11], but it is a representative combination for electricity production in Canada over a number of years. The trend is the reduction of contribution by coal and natural gas, and the increase of renewable energy such as hydropower and wind.

The energy use and emissions of electricity generation are needed in GREET for two purposes: electricity usage of upstream fuel production activities and electricity use in electric vehicles (EVs) and grid-connected hybrid electric vehicle (HEVs). The GREET model calculates emissions associated with electricity generation from residual oil, NG, coal, and uranium. Electricity generated from hydropower, solar energy, wind, and geothermal energy is treated as having zero emissions; these sources are categorized together in one group, called others [3].

The default inputs of GREET were used in order to analyze the fuel cycle discussed in this study.

The analysis of the "vehicle cycle" was carried out using published data from literature. This data was used in a series of equations to obtain the final results presented later in this paper. The material production energy for producing 100% virgin material and 100% recycled material was found from Schucker et al. [10], as shown in Tables 2 and 3.

The material production energy used for the 30% recycled and 70% virgin material is simply 30% of the energy associated with 100% recycled material plus 70% of the energy associated with the 100% virgin material as shown in Table 4.

In order to estimate the emissions of carbon dioxide for material production, two emission factors are examined; one for thermal energy (by fuel) and another one for electricity generation. For the energy directly supplied by fossil fuels, the emission factor of oil is assumed to be 20.9 kgC GJ^{-1}. In the case of primary steel making, the emission factor used

Table 1
Canadian electricity mix used in GREET [3]

Residual oil (%)	0
Natural gas (%)	32.9
Coal (%)	21.3
Nuclear power (%)	14.7
Others (%)	31.1

Table 2
Material production energy breakdown for 100% virgin material

Material	Energy (kJ kg^{-1})
Ferrous materials	39,400
Copper	100,000
Zinc	53,000
Lead	41,100
Aluminum	192,500
Magnesium	284,000
Glass	25,500
Fluids	62,733
Rubber	67,600
Plastics	200,040
Other	138,163

Table 3
Material production energy breakdown for 100% recycled material

Material	Energy (kJ kg^{-1})
Ferrous materials	18,690
Copper	45,000
Zinc	15,900
Lead	8,000
Aluminum	26,350
Magnesium	27,200
Glass	13,000
Fluids	62,733
Rubber	43,600
Plastics	43,427
Other	124,425

Table 4
Material production energy breakdown for 70% virgin 30% recycled material

Material	Energy (kJ kg^{-1})
Ferrous materials	33,187
Copper	83,500
Zinc	41,870
Lead	31,170
Aluminum	142,655
Magnesium	206,960
Glass	21,750
Fluids	62,733
Rubber	60,400
Plastics	153,056
Other	134,041

is 23.3 kgC GJ^{-1}[1] (the average of coal and oil). For electricity supplied while producing the primary metal, the release is 54 kgC GJ^{-1} of electricity supplied. Fifteen percent of the energy used to produce primary steel is obtained through electricity. Seventy-five percent of the energy used to produce aluminum is obtained from electricity. The emission factors of carbon while manufacturing other material are not considered in this study.

The assembly energy used in this analysis is based on relating the energy to the mass of the vehicle linearly. The energy needed to produce an automobile ranges from 17,400 to 22,100 kJ kg^{-1} [10]. The average of these two energies is used to obtain the results presented in this study. The emission factors of vehicle assembly are assumed on the basis that 50% of the consumed energy is from electricity and the remaining energy is directly used from oil. The emission factors used are 54 kgC GJ^{-1} for electricity and 23.3 kgC MJ^{-1} for oil [10].

The distribution energy is estimated by using an average transportation distance of 1600 km and an average energy consumption rate of 600 J $(kg\,km)^{-1}$. Disposal Energy is assumed to be 370 kJ kg^{-1} [10]. The emissions associated with the distribution and disposal energies are neglected in this study since they are very small in comparison to the emissions associated with material production and vehicle assembly. The emissions associated with the distribution step could be estimated as the emissions from the use of heavy duty trucks.

The equations used for this analysis are listed below. The energy consumption of the material production step is calculated as follows:

$$EC_{MATRL} = E_{MATRL}(kJ\,kg^{-1}) \times M_{MATRL}(kg) \quad (1)$$

where EC_{MATRL} is the total energy consumption of the material during the production process, E_{MATRL} the energy consumption of the material per kilogram during the production process and M_{MATRL} is the total mass of the materials (kg). The energy consumption during vehicle assembly step is estimated from:

$$EC_{ASSY} = 19,750\,(kJ\,kg^{-1}) \times M_{VEHICLE}\,(kg) \quad (2)$$

The energy consumption for the vehicle disposal step is determined by:

$$EC_{DISP} = 370\,(kJ\,kg^{-1}) \times M_{VEHICLE}\,(kg) \quad (3)$$

where $M_{VEHICLE}$ represents the total mass of the vehicle and EC stands for the energy consumption for the respective steps involved. The energy consumption for vehicle distribution is calculated from:

$$EC_{DIST} = 600\,(J\,(kg\,km)^{-1}) \times 600\,(km) \times M_{VEHICLE}\,(kg) \quad (4)$$

The carbon dioxide emissions associated with the production of steel, CO_2E_{STEEL}, is estimated as follows:

$$CO_2E_{STEEL} = \left(\frac{44}{12}\right) \times CE_{STEEL}\,(kgC) \quad (5)$$

where CE_{STEEL} is the carbon emissions during the production of steel and is found from:

$$CE_{STEEL} = EC_{STEEL}\,(MJ) \times \Big[0.0233\,(kgC\,MJ^{-1}) \times 0.85 + 0.15 \times 0.054(kgC\,MJ^{-1})\Big] \quad (6)$$

The carbon dioxide emissions associated with the production of aluminum, CO_2E_{AL}, is determined as:

$$CO_2E_{AL} = \left(\frac{44}{12}\right) \times CE_{AL}(kgC) \quad (7)$$

where CE_{AL} is the carbon emissions during the production of aluminum, and is estimated from:

$$CE_{AL} = EC_{AL}(MJ) \times \Big[0.0209\,(kgC\,MJ^{-1}) \times 0.25 + 0.75 \times 0.054\,(kgC\,MJ^{-1})\Big] \quad (8)$$

The carbon dioxide emissions related to the vehicle assembly step are calculated as follows:

$$CO_2E_{ASSY} = \left(\frac{44}{12}\right) \times CE_{ASSY}\,(kgC) \quad (9)$$

where the carbon emissions during the vehicle assembly is estimated from the following equation:

$$CE_{ASSY} = EC_{ASSY}\,(MJ) \times \Big[0.5 \times 0.0233(kgC\,MJ^{-1}) + 0.5 \times 0.054\,(kgC\,MJ^{-1})\Big] \quad (10)$$

6. Results and discussion

6.1. Vehicle life cycle

The analysis is first carried out for the vehicle life cycle. This part of the analysis consists of the sequence in which the vehicle itself goes through (material production, assembly, distribution, and disposal). Each of these four steps contributes to the total energy use and emissions throughout the vehicle life cycle. The material production step is very much dependent upon the average weight of each material being used in the vehicle. The remaining three steps on the other hand are very much dependent upon the total weight of the vehicle itself. The analysis shows that the material production step is responsible for almost 75% of the energy consumption and emissions during the vehicle life cycle, as illustrated in Table 5.

As it can be seen from the table, the total energy consumption and GHG emissions for the vehicle life cycle are relatively the same for ICEV and FCV. The slight difference

[1] The Carbon Emission Factor of Oil was found from reference [5]. In the reference text, the emission factor is listed as 23.3 kgC/MJ. However, it is believed that there is a mistake in the units and the emission factor should be 23.3 kgC/GJ.

Table 5
Contribution of each step to the vehicle life cycle

	Gasoline (ICEV)			Hydrogen (FCV)		
	Energy use (GJ)	Emissions (tonC)	Emissions (tonCO_2)	Energy use (GJ)	Emissions (tonC)	Emissions (tonCO_2)
Material production	93.73	1.69	6.19	95.84	1.69	6.19
Assembly	25.42	0.99	3.62	25.08	0.97	3.57
Disposal	0.49	0	0	0.48	0	0
Distribution	0.48	0	0	0.47	0	0
Total	120.12	2.67	9.81	121.87	2.66	9.76

Table 6
Weight distribution of present ICEV and FCV

	Gasoline ICEV		Hydrogen FCV	
Material	Mass (kg)	Energy (kJ)	Mass (kg)	Energy (kJ)
Ferrous materials	886	34,908,400	886	34,908,400
Copper	9	900,000	9	900,000
Zinc	7	371,000	7	371,000
Lead	10	411,000	–	–
Aluminum	81	15,592,500	81	15,592,500
Magnesium	10	2,840,000	10	2,840,000
Glass	35	892,500	35	892,500
Fluids	54	3,387,600	6	376,400
Rubber	54	3,650,400	54	3,650,400
Plastics	100	20,004,000	100	20,004,000
Other	78	10,776,675	118	16,303,175
Total	1324	93,734,075	1306	95,838,375

between the two vehicles is due to differences in weight distribution of materials, as shown in Table 6.

The effect of recycling on the vehicle life cycle is also considered in this study. Tables 7–9 show that the total energy consumption and total GHG emissions are lower with recycled material than with virgin material. We can see here again that the material production step is responsible for more than 60% of the total energy consumption and the total GHG emissions.

Even though the method of recycling seems very appealing, the use of recycled material is normally limited to 20–30% in the manufacturing of vehicles. This is due to the desire for better finish on the parts as well as the desire to optimize the material properties [12,13]. The use of 100% recycled material results in a 45% decline of energy consumption and a 42% decline in carbon dioxide emissions. While the use of 30% recycled material results in a 13% decrease of energy consumption and a 13% decrease of carbon dioxide emissions.

Finally, the future vehicle is estimated to have a less average weight than the present vehicle as well as a higher average weight of aluminum. The use of aluminum is expected to rise since it is less in density than steel. This makes the vehicle lighter. Lighter vehicles are expected to be more fuel efficient since less weight has to be supported. The trend of the increase in the use of aluminum in vehicles is shown in Fig. 1 [14].

This study evaluates the life cycle of present and future ICEV and FCV. Table 10 shows that the total mass of the future vehicle is less than that of the present vehicle. It is also noticeable that approximately four times as much aluminum is used in the future vehicle. Fig. 2 is a comparison between the present and future ICEV in terms of energy consumption. As it can be seen the total energy consumption is 20% higher for the future ICEV. This is due to 30%

Table 7
Contribution of Each Step to the Vehicle Life Cycle with the use of 30% recycled material

	Gasoline (ICEV)			Hydrogen (FCV)		
	Energy use (GJ)	Emissions (tonC)	Emissions (tonCO_2)	Energy use (GJ)	Emissions (tonC)	Emissions (tonCO_2)
Material production	77.56	1.35	4.95	79.59	1.35	4.95
Assembly	25.42	0.99	3.62	25.08	0.97	3.57
Disposal	0.49	0	0	0.48	0	0
Distribution	0.48	0	0	0.47	0	0
Total	103.94	2.34	8.57	105.62	2.32	8.52

Table 8
Contribution of each step to the vehicle life cycle with the use of 100% recycled material

	Gasoline (ICEV)			Hydrogen (FCV)		
	Energy use (GJ)	Emissions (tonC)	Emissions (tonCO_2)	Energy use (GJ)	Emissions (tonC)	Emissions (tonCO_2)
Material production	39.81	0.56	2.05	41.69	0.56	2.05
Assembly	25.42	0.99	3.62	25.08	0.97	3.57
Disposal	0.49	0	0	0.48	0	0
Distribution	0.48	0	0	0.47	0	0
Total	66.19	1.55	5.67	67.72	1.53	5.62

Table 9
Energy use and emission % differences (100% virgin material is taken as the base)

	Present							
	Gasoline ICEV				Hydrogen FCV			
	Energy		CO_2 Emissions		Energy		CO_2 Emissions	
Material used	GJ	% Difference	ton	% Difference	GJ	% Difference	ton	% Difference
100% Virgin	120.12	0	9.81	0	121.87	0	9.76	0
30% Recycled, 70% virgin	103.94	−13	8.57	−13	105.62	−13	8.52	−13
100% Recycled	66.19	−45	5.67	−41	67.72	−44	5.62	−42

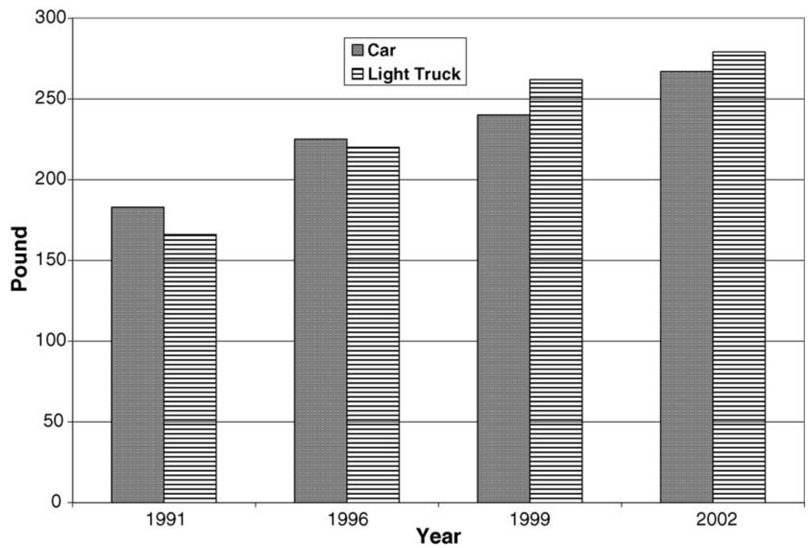

Fig. 1. Aluminum use in vehicles over the years [14].

higher material production energy. The material production energy is increased due to the increased use of aluminum in the vehicle. Similarly, Fig. 3 shows the comparison between the present and future FCV in terms of energy consumption. Again, the total energy consumption is 20.7% higher for the future FCV. This is due to an increase of 32% in the energy consumption for the material production. It might be pointed out that the energy consumption associated with the disposal and distribution of FCV is so small that it looks like zero in Fig. 3.

6.2. Fuel life cycle

The analysis of the fuel life cycle has been conducted using GREET. GREET is a software that has been created by Argonne National Laboratories in order to analyze the life

Table 10
Weight distribution of present and future ICEV and FCV

Material	Passenger vehicle present		Passenger vehicle future	
	Gasoline ICEV	Hydrogen FCV	Gasoline ICEV	Hydrogen FCV
	Mass (kg)	Mass (kg)	Mass (kg)	Mass (kg)
Ferrous materials	886	886	325	325
Copper	9	9	9	18
Zinc	7	7	3	3
Lead	10	–	10	–
Aluminum	81	81	342	342
Magnesium	10	10	20	20
Glass	35	35	35	35
Fluids	54	6	36	4
Rubber	54	54	50	50
Plastics	100	100	100	99
Other	78	118	78	118
Total	1324	1306	1008	1014

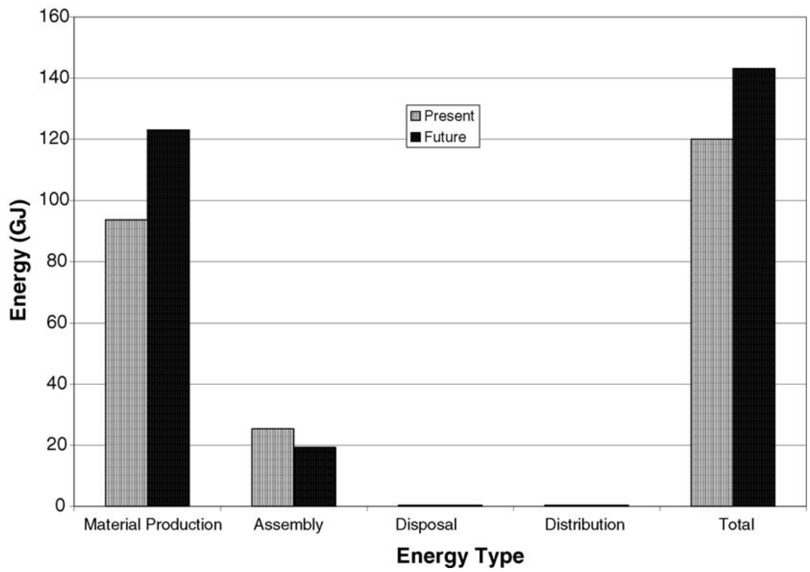

Fig. 2. Energy consumption during the vehicle life cycle of a present and future ICEV.

cycle of a fuel. It takes into account many different inputs to obtain the energy needed and the emissions associated with the well-to-wheel cycle of the fuel. The well-to-wheel cycle is simply the sequence of obtaining the raw material of the fuel, treating it, transporting and storing the fuel as well as consuming the fuel. GREET considers the following in its analysis:

- the nature of the raw material needed to produce the fuel (for example, NG to obtain hydrogen and petroleum to obtain gasoline);
- the transportation method and distance;
- the electricity mix (US/Canadian);
- the method of obtaining electricity, such as via nuclear power, solar energy, etc. . .

Fig. 4 was created using GREET in order to compare the energy consumption and GHG emissions during the life cycle of hydrogen obtained by the four different methods and the life cycle of conventional gasoline. The four different hydrogen production methods include using coal and nuclear power to produce electricity first and then extract hydrogen through electrolysis, and via steam reforming of natural gas in a natural gas central plant and in a hydrogen refueling station.

It is obvious that the extraction of hydrogen via electrolysis using nuclear power leads to the lowest emissions. This is due to the fact that there is no carbon emission in obtaining the nuclear power required. GREET assumes that the emissions of carbon in obtaining nuclear power is solely based on mining, transporting, and enriching uranium. In addition, extracting hydrogen from coal requires the highest energy

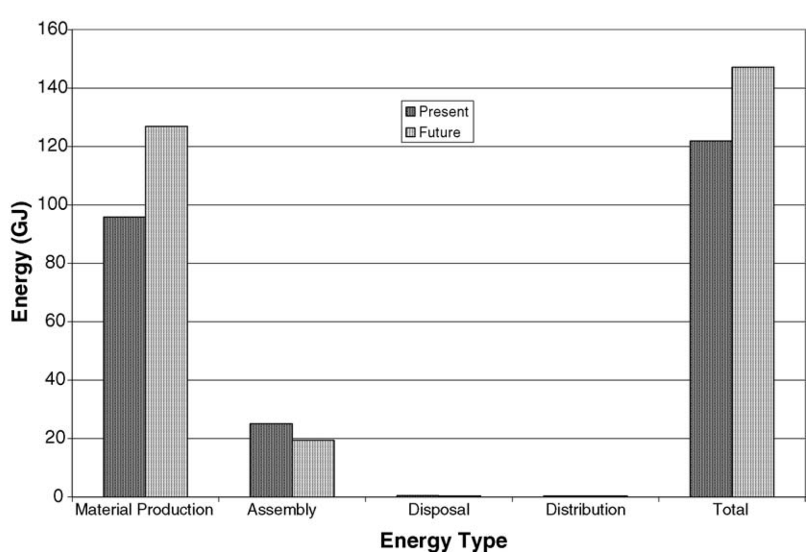

Fig. 3. Energy consumption during the vehicle life cycle of a present and future FCV.

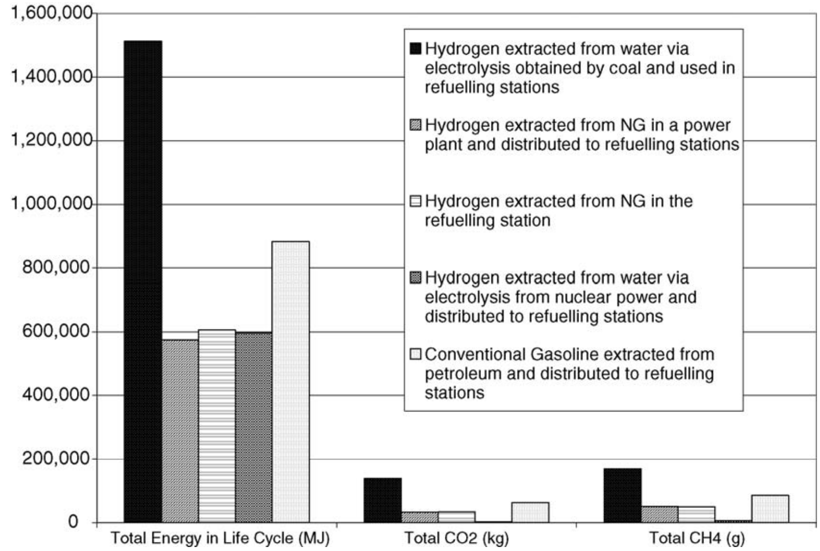

Fig. 4. The total energy and GHG emissions during the entire fuel life cycle (300,000 km)—GREET.

consumption and results in the highest emissions. Extracting hydrogen from natural gas in the refueling station requires approximately the same amount of energy and emits approximately the same emissions as extracting hydrogen in a central natural gas plant.

In addition, GREET was used to analyze the energy consumption and emissions associated with the present and future gasoline, given in Fig. 5. It is clear that the energy and emissions are lower under the long-term conditions. This is due to the higher engine efficiency and higher electricity use efficiency. The future vehicles are assumed to have better engine efficiency and assumed to have better fuel efficiency. Future vehicle is assumed to travel 27.4 mile gal^{-1} and the present is assumed to travel 22.4 mile gal^{-1} (GREET).

6.3. *Efficiency of ICEV and FCV*

The total efficiency of ICEV and FCV consists of the well-to-tank efficiency and the tank-to-wheel efficiency. The well-to-tank efficiency of an ICEV is 80%. The well-to-tank efficiency of a FCV depends largely on the method of obtaining hydrogen. Fig. 6 shows the well-to-tank efficiency of the methods considered in this study.

The tank-to-wheel efficiencies are 17.1 and 36% for an ICEV and a FCV, respectively [5]. The total efficiency is shown in Fig. 7. This figure shows that extracting hydrogen via NG is the most efficient. Overall, the FCV is more efficient than the ICEV. The well-to-wheel efficiencies are 21.7 and 13.8% for a FCV and an ICEV, respectively.

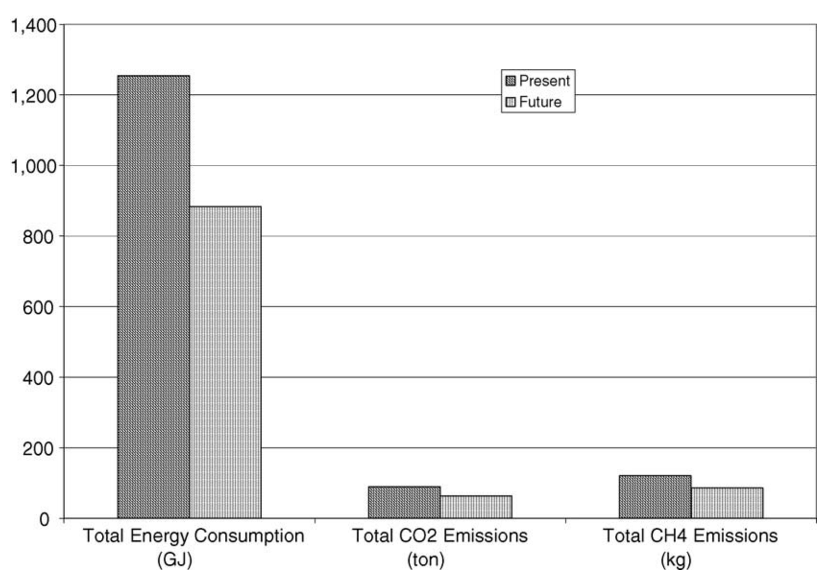

Fig. 5. Energy consumption and GHG emissions during gasoline life cycle under near and long term conditions—GREET.

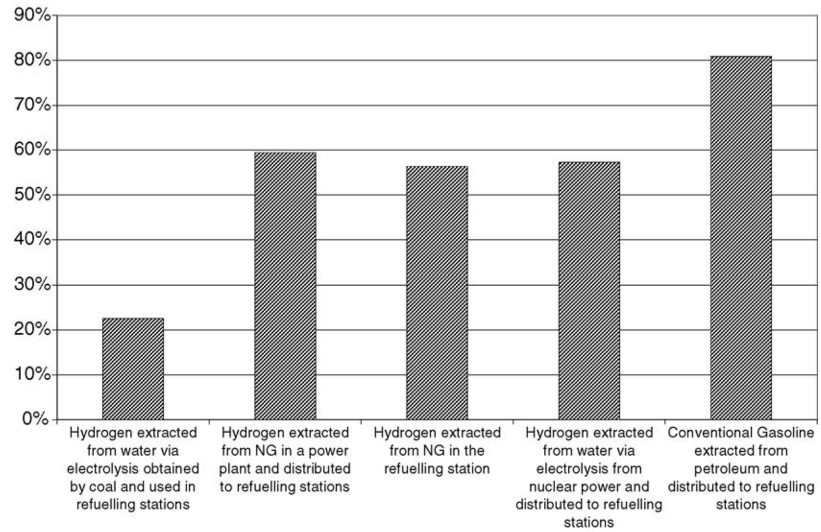

Fig. 6. Well-to-tank efficiency.

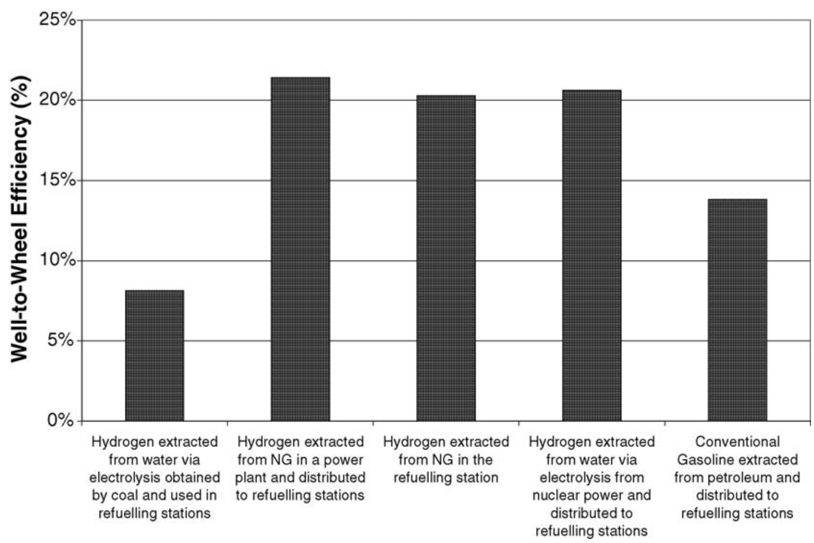

Fig. 7. Well-to-wheel efficiency.

6.4. Total life cycle of an ICEV and an FCV

The study shows that the FCV vehicle will have lower emissions than the ICEV as summarized in Tables 11 and 12 for the present and future vehicles, respectively. In order to compare the ICEV and FCV, the tables show the energy and emissions percentage difference taking the ICEV as the base.

The emissions are lower for the FCV since the electro-oxidation process of hydrogen is not associated with any carbon dioxide emissions, while on the other hand the burning of conventional gasoline is. As it can be seen, the contribution of the fuel life cycle to the total life cycle is much more for gasoline than it is for hydrogen.

As expected, it can be seen that extracting hydrogen via electrolysis from coal generates the highest emissions and consumes the most energy in comparison with the other methods. Under the present conditions, extracting hydrogen via electricity from coal results in a total energy consumption by the FCV of 19% higher than an ICEV and a total emission of 50% more carbon dioxide. Similarly, under the future conditions, the FCV run on hydrogen extracted from electricity via coal will consume 62% more energy and emit 98% more carbon dioxide than an ICEV. Therefore, if hydrogen is to become the primary fuel on the road, the use of coal to obtain hydrogen should be minimized. The use of nuclear power and natural gas to extract hydrogen has similar energy consumption but using nuclear power to extract hydrogen leads to less emissions. Under the present conditions, the energy consumption by FCV with hydrogen extracted via the nuclear power method is almost half of that of ICEV and the total carbon dioxide emissions are almost 87% lower for FCV than ICEV. For an FCV with hydrogen extracted via the NG method, the total energy consumption and total emissions are half of that of ICEV. Similarly, under the future condi-

Table 11
Total energy consumption and total emissions (present vehicle)

Method	Fuel life cycle (GJ)	Total CO_2 (ton)	Vehicle life cycle (GJ)	Total CO_2 (ton)	Total energy in life cycle (GJ)	Total CO_2 (ton)	Energy (%)	Emissions (%)
Hydrogen extracted from water via electrolysis obtained by coal and used in refuelling stations	1513	139.41	121.87	9.76	1635	149	19	50
Hydrogen extracted from NG in a power plant and distributed to refuelling stations	575	32.49	121.87	9.76	697	42	−49	−57
Hydrogen extracted from NG in the refuelling station	607	34.43	121.87	9.76	729	44	−47	−55
Hydrogen extracted from water via electrolysis from nuclear power and distributed to refuelling stations	597	2.97	121.87	9.76	719	13	−48	−87
Conventional Gasoline extracted from petroleum and distributed to refuelling stations	1255	89.44	120.12	9.81	1375	99	0	0

tions, the energy consumption by a FCV running on hydrogen extracted via the nuclear power method is 27% lower than that of an ICEV and the carbon dioxide emissions are lower by 77%. For an FCV running on hydrogen extracted via the NG method, the total energy consumption is 27% less than that of ICEV and the total emissions are 37% lower than that of ICEV.

The total energy consumption of the future ICEV is 25% less than the total energy consumption of the present ICEV. This is mostly due to the change in gasoline production and to reducing the overall weight of the vehicle. The total carbon dioxide emissions of the future ICEV are 21.4% less than the present ICEV. The total energy consumption of the future FCV is 3.5% higher than that of the present FCV, due to the increased aluminum content for lighter vehicles. The total carbon dioxide emissions of the future FCV are 12.1% higher than that of the present FCV.

6.5. Price of ICEV and FCV

When comparing the two types of vehicles (ICEV and FCV), it is very important to study the price difference. As mentioned before the weight of the vehicles will approximately be the same; the weight of the fuel cell stack will approximately be similar to that of the internal combustion engine. Therefore, it is reasonable to assume the same base price for both vehicles. In order to estimate the price of a fuel cell vehicle, one needs to add the prices of the additional parts and subtract the parts that will no longer be used in the vehicle. The typical pricing method of fuel cell power stacks will be on a US$ kW^{-1} basis since the larger power stacks will require more of the same components at a linear cost. It is assumed that the cost of the control, instrumentation and diagnostic system will be small in comparison so that the cost of fuel cell power unit can be treated as being linear; the price that will be used in this analysis is US$ 50 kW^{-1}. Currently, the price of a fuel cell stack is approximately US$ 5,000–10,000 kW^{-1}. However, with improved technology and research and development, the price will be lowered to that of US$ 30–70 kW^{-1} [15].

A mechanical system is not considered in the comparison below. This is due to the operation method of the fuel cell vehicle. In fuel cell powered vehicles, the fuel cell system is combined with a battery. The battery will allow the passen-

Table 12
Total energy consumption and total emissions (future vehicle)

Method	Fuel life cycle (GJ)	Total CO_2 (ton)	Vehicle life cycle (GJ)	Total CO_2 (ton)	Total energy in life cycle (GJ)	Total CO_2 (ton)	Energy (%)	Emissions (%)
Hydrogen extracted from water via electrolysis obtained by coal and used in refuelling stations	1512.87	139.41	147.12	15.12	1659.98	154.53	62	98
Hydrogen extracted from NG in a power plant and distributed to refuelling stations	575.11	32.49	147.12	15.12	722.23	47.61	−30	−39
Hydrogen extracted from NG in the refuelling station	606.94	34.43	147.12	15.12	754.06	49.55	−27	−37
Hydrogen extracted from water via electrolysis from nuclear power and distributed to refuelling stations	597.29	2.97	147.12	15.12	744.41	18.09	−27	−77
Conventional Gasoline extracted from petroleum and distributed to refuelling stations	882.98	62.96	143.19	15.10	1026.17	78.06	0	0

Table 13
Price of an ICEV and a future FCV in Canadian dollars

Propulsion system	SI ICE	FC hybrid
Fuel	Gasoline	Hydrogen
Vehicle type	Passenger	Passenger
Baseline vehicle	US$ 21,717.65	US$ 21,717.65
Engine		
Credit for downsizing		−US$ 6000.00
Fuel cell systems		
Fuel cell		US$ 5195.04
Fuel tank		US$ 975.00
Electric motor		US$ 1558.51
Single stage red. transm.		US$ 226.50
Battery		US$ 2597.52
Exhaust gas cleaning		−US$ 645.00
Vehicle		
Weight reduction		US$ 2400.00
Aerodynamics		US$ 225.00
Total vehicle price	US$ 21,717.65	US$ 28,250.22

ger to maintain fuel cell operation in its high efficiency (part load) region as much as possible and benefit from regenerative braking energy recovery. During idling and low power operation, the batteries supply the necessary power. Over a certain threshold, the fuel cell turns on; extra power is used to recharge the batteries if they are below a set state of charge. When the power required exceeds the maximum fuel cell stack capabilities, the batteries again supplements peak loading. Since the fuel cell directly converts chemical energy to electrical energy, a mechanical transmission is not required [5].

The estimated capital price of the ICEV and FCV is presented in Table 13. As it is seen, the FCV is more expensive than the ICEV, because the fuel cell power unit is more expensive than the internal combustion engine unit plus the exhaust gas cleaning. Therefore, the cost reduction of the fuel cell power unit is crucial to the total cost reduction of a FCV. Although FCV is more expensive than the ICEV at first glance, it will not be the case during the entire operational life of the vehicle. The prices presented in Table 13 are the capital prices of the vehicles (i.e., the estimated purchasing cost of the vehicle). However, the much higher well-to-wheel efficiency of FCV (22%) as compared to ICEV (14%) will result in much lower operating cost for FCV such that over the vehicle lifetime the FCV would be cheaper in overall costs (the sum of capital cost, operation, and maintenance cost).

These dollar figures, shown in Table 13, have been obtained from many different sources. The price of the baseline vehicle is an average price of General Motors (GM) passenger vehicles sold in Canada. The engine price is also obtained from GM; the engine is capable of providing 140 hp (approximately 104 kW). The fuel cell power unit is also capable of providing the same power and is rated at US$ 50 kW^{-1}. The other figures are estimates obtained from Weiss et al. [5] and have been converted from USD to CAD with a conversion factor of 1.5CAD/USD.

7. Challenges facing the hydrogen economy

From the preceding analysis, it is clear that compared to the conventional gasoline fuelled ICEVs, fuel cell vehicles using hydrogen as fuel have substantially better overall life cycle (well-to-wheel, or cradle to grave) energy efficiency as well as lower GHG emissions, provided that hydrogen is produced from electrolysis with nuclear energy, or steam reformed from natural gas. This suggests the viability of hydrogen fuel cells, or indirectly the so-called hydrogen economy. However, there are many challenges that are facing the realization of the hydrogen economy. Some of those challenges are summarized below.

1. The "best" or optimal method of obtaining hydrogen must be determined. The industry must identify the production methodology or pathway keeping in mind the following constraints: safety, cost, emissions, energy consumption, reliability, efficiency, and availability.
2. The transportation and storage of hydrogen should be addressed. The new infrastructure should be designed. The constraints that should be kept in mind are as follows: cost, efficiency, and safety. In order to be able to identify the best infrastructures, the method of obtaining hydrogen and the state of hydrogen (i.e., liquid or gaseous fuel) should be identified first.
3. There are many issues facing the manufacturing sector:
   a. The manufacturer should be able to market the new vehicles. Cost, safety, reliability, and efficiency issues should be addressed. The average consumer is interested in a product that will be as good or better as the product it is replacing.
   b. Technological issues are also faced. The new market will be very competitive. Manufacturers should be able to identify the best technology to be used in their new vehicles.
   c. Fuel cell systems should be addressed. More research and development should be carried out in order to reduce the cost of the systems and increase their efficiency. Different technologies should be studied in order to store the excess power created by the fuel cells and use them at a later time (e.g., the use of batteries to store excess power).
4. Safety issues should be addressed by government through the enactment of the codes and standards. The government should identify all the safety levels of greenhouse gas emissions, fuel safety, new local safety, and zoning requirements for fueling stations.
5. The government must be involved in the new change. Procedures of change of infrastructures should be designed and put in place by the government.
6. The federal and provincial tax incentives (or fair taxes) should be identified and put in place for the distribution of hydrogen as a widely used fuel.
7. The government must identify how the hydrogen economy will be introduced to the public. Will the government be

willing to subsidize vehicle owners the difference in price between fuel cell vehicles and internal combustion engine vehicles?

8. Conclusions

A full life cycle analysis for vehicles powered by the conventional internal combustion engines fuelled by gasoline and fuel cells fuelled by hydrogen has been conducted with the economic and energy realities in Canada, including both the “fuel cycle” and “vehicle cycle”. Four different methods (or pathways) for the production of hydrogen are also evaluated, including:

- using coal as the primary energy source to produce electricity first and then produce hydrogen through electrolysis;
- using nuclear power to produce electricity first and then produce hydrogen through electrolysis;
- steam reforming of natural gas in a natural gas central plant and then distributing hydrogen to a hydrogen refueling station;
- steam reforming of natural gas in a hydrogen refueling station directly.

The analysis carried out in this study shows that FCV is a better choice than ICEV except for hydrogen production using coal as the primary energy source. For the today’s vehicles, if hydrogen is extracted via steam reforming of natural gas or the use of electricity from nuclear power, the energy consumption by a FCV is 50% lower than that of an ICEV. The total carbon dioxide emission is 77% lower in a FCV than that of an ICEV if hydrogen is extracted from steam reforming of natural gas. If hydrogen is extracted via the use of electricity from nuclear power, the emissions are lowered and are 87% lower than that of an ICEV. However, if hydrogen were to be extracted using electrolysis via coal the energy consumption of a FCV is 19% higher than that of an ICEV and the emissions are 50% higher than an ICEV. Similarly, for the future vehicles, if hydrogen is extracted via steam reforming of natural gas or the use of electricity from nuclear power, the energy consumption by a FCV is 27% lower than that of an ICEV. The total carbon dioxide emission is 37% less for a FCV when hydrogen is extracted from steam reforming of NG. When hydrogen is extracted from electricity via nuclear power, the emissions of the future FCV will be 77% lower than that of the future ICEV. Again, if hydrogen were to be extracted using electrolysis via coal, the energy consumption of the FCV is 62% higher than that of an ICEV and the total carbon dioxide emissions are 98% higher than that of an ICEV.

Recycling of materials where possible is desired nowadays. The analysis presented shows that the use of 100% recycled material results in a 45% decrease in emissions compared with using 100% virgin material. Similarly, the use of 100% recycled material can consume up to 45% less energy than the use of 100% virgin material. However, the use of 100% recycled material for every part of the vehicle is very unlikely due to the change in material properties via recycling. The manufacturing industry is currently using 20–30% recycled material in some vehicles. The use of 30% recycled material translates to a 13% decrease in energy consumption and a 13% decrease in carbon dioxide emissions.

The well-to-wheel efficiency of a fuel cell vehicle run by hydrogen obtained via natural gas is 21%, while the well-to-wheel efficiency of an internal combustion engine vehicle run by conventional gasoline is 13.8%. This is so since the FCV vehicle is much more efficient during the pump-to-wheel stage (FCV pump-to-wheel is 36%, while ICEV pump-to-wheel is 17.1%).

Even though the capital cost of a FCV is estimated to be higher than the cost of ICEV by around CAD$ 6500 CAD, the higher FCV efficiency will compensate for that difference with lower operating costs. Therefore, the cost of the FCV is expected to be lower than the ICEV over their entire lifetime.

Finally, before moving forward and replacing all the ICEVs on the road with FCVs many issues have to be resolved. Issues such as government involvement, infrastructure, state of hydrogen, and many technological issues should be addressed.

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