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Life cycle comparison of fuel cell vehicles and internal combustion engine vehicles for Canada and the United States

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Abstract

The objective of this study is to put forward a full analysis of the impact of the difference between the Canadian and American energy realities on the life cycle of fuel cell vehicles and internal combustion engine vehicles. Electricity is a major type of energy used in the transportation sector. Electricity is needed in the production of feedstock of fuel, the production of the fuel, the production of the vehicle material and the assembly of the vehicles. Therefore, it is necessary to investigate the impact of the electricity mix difference between Canada and the United States. In the analysis, 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 extract 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 fuel cell vehicle fuelled by hydrogen has lower energy consumption and greenhouse gas emissions than internal combustion engine vehicle fuelled by conventional gasoline except for hydrogen production using coal as the primary energy source in Canada and the United States. Using the Canadian electricity mix will result in lower carbon dioxide emissions and energy consumption than using the American electricity mix. For the present vehicles, using the Canadian electricity mix will save up to 215.18 GJ of energy and 20.87 t of CO_2 on a per capita basis and 26.53 GJ of energy and 6.8 t of CO_2 on a per vehicle basis. Similarly, for the future vehicles, using the Canadian electricity mix will lower the total carbon dioxide emissions by 21.15 t and the energy consumed is reduced by 218.49 GJ on a per capita basis and 26.53 GJ of energy and 7.22 t of CO_2 on a per vehicle basis. The well-to-tank efficiencies are higher with the Canadian electricity mix.

Keywords: Fuel cell vehicle; Internal combustion engine vehicle; Life cycle analysis; Energy efficiency; Canadian electricity mix; American electricity mix

1. Introduction

There has been a major concern in the need to decrease the carbon dioxide emissions in all energy sectors because of health hazards and local/global environmental degradation. In Canada and the United States, the transportation sector is very energy demanding and therefore the carbon dioxide emissions associated with it are very high. In Canada, the transportation sector was responsible for 34% of the total emissions by all sectors in year 2002 (160 million metric tonnes) [1]. In the United States, the transportation sector accounted for 32.4% of the total US energy related carbon dioxide emissions in 2003 (1874.7 million metric tonnes) [2]. Even though, there is a difference in the total carbon dioxide emitted by the transportation sector in both countries, the total percentages are very similar. In addition, studying the trend of the carbon dioxide emissions increase, it can be seen that the trend in both Canada and the United States is very similar. Since 1990, the carbon dioxide emissions related to transportation has increased at a rate of 1.1 [1] and 1.4% [2] annually in Canada and the United States, respectively. Therefore, it is obvious that the transportation sector behaves in a similar fashion in Canada and the United States.

The increased carbon dioxide emissions by the transportation industry in both countries have led to the need of alternative solutions. One of the most discussed solutions is the use of hydrogen fuel cells instead of gasoline internal combustion engines to power vehicles. The use of proton exchange membrane fuel cells (PEMFC) is very attractive since the only byproduct of the chemical reactions is pure water. Much research on PEMFC is still ongoing. In order to be able to commercialize fuel cell

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vehicles, the performance and efficiency of PEMFC should be maximized. Despite the promises and the extensive research of fuel cell vehicles, concerns have been raised about the hydrogen economy in general and fuel cell technology. In particular, Wald [3] argued that all research efforts should be converted entirely towards other green technologies, such as wind and solar power. His argument focused entirely on the obstacles surrounding fuel cell commercialization, such as infrastructure and cost. Kreith and West [4] presented an argument against the fuel cell and hydrogen economy based on the obstacles surrounding them. Similar concerns and analysis have been raised by others as well, e.g. references [5] and [6].

However, our previous study [7] on the life cycle of vehicles powered by fuel cells or internal combustion engines [7] indicates that among several scenarios of hydrogen production and distribution, hydrogen fuel cell powered vehicles would have much higher overall energy efficiency and much less greenhouse gas emissions when compared to the conventional internal combustion engine driven vehicles, except the scenario of hydrogen production via electrolysis of water with electricity generated in a thermal power plane burning coal as the primary fuel. The full life cycle analysis of the fuel cell vehicles (FCV) and internal combustion engine vehicles (ICEV) in the previous study suggests that the use of hydrogen fuel cells in vehicles will reduce carbon dioxide emissions by as much as up to 49% [7]. Further, hydrogen fuel cell vehicles are clean without emissions at the point of use, potentially to alleviate pollution in urban areas and hence they are considered the integral part of future diversified energy systems [8]. Recently, analysis has been carried out for the life cycle assessment, impacts assessment and trade-offs for solid oxide fuel cell-based auxiliary power units when they are used for non-propulsion purposes for diesel engine powered vehicles [9–12]. It was found [9] that the total amount of pollutants that are released during the life cycle of the auxiliary power units is much less than in the case of idling of diesel engines.

The present study extends the full life cycle analysis for FCV and ICEV manufactured and used in Canada and in the United States. The objective is to compare the impact of the difference between the Canadian and American energy realties on the life cycle of fuel cell vehicles and internal combustion engine vehicles.

2. Scope

This study has been designed to put forward a comparison of the total life cycle of fuel cell vehicles and internal combustion engine vehicles in Canada and the United States. Different fuels and vehicle technologies are used in this analysis and they are described below.

Fuels:

A. In this case, hydrogen is obtained via natural gas (NG) reforming in a central power plant. The hydrogen produced is then distributed to hydrogen refueling stations via pipelines. Therefore, the steps considered in the analysis for this case are as follows:
   - production of natural gas;
   - transportation of natural gas to steam reforming plant (central power plant);
   - steam reforming of natural gas and obtaining hydrogen;
   - distribution of hydrogen to hydrogen refueling stations via pipelines.

B. In this case, electricity is obtained from a coal fired power plant and is used to perform electrolysis on water to extract hydrogen. The steps involved are:
   - production of coal (feedstock);
   - transportation of coal to coal fired power plant;
   - using coal combustion to produce electricity;
   - splitting water via electrolysis using the electricity to produce hydrogen;
   - distribution of hydrogen to refueling stations via pipelines.

C. This case considers the use of nuclear power to generate electricity to be used to electrolyze water for hydrogen production. The steps are:
   - production of uranium;
   - transportation of uranium to uranium enrichment/processing plant;
   - enrichment of uranium;
   - using uranium in nuclear power plant to produce electricity;
   - splitting water via electrolysis using the electricity to obtain hydrogen;
   - distribution of hydrogen to refueling stations via pipelines.

D. In this case, steam reforming in the hydrogen refueling station is considered for hydrogen production. The steps considered include:
   - production of natural gas;
   - transportation of natural gas to hydrogen refueling stations;
   - steam reforming of natural gas in hydrogen refueling station.

Table 1
Summary of fuels under study

Fuel	Description
A	Hydrogen from the steam reforming of natural gas in a central plant
B	Hydrogen from the electrolysis of water with electricity generated in a coal-burning thermal power plant
C	Hydrogen from the electrolysis of water with electricity generated in a nuclear power plant
D	Hydrogen from the steam reforming of natural gas in a hydrogen refueling station
E	Conventional gasoline

E. This case involves extracting gasoline from crude oil and the steps are:
   - production of crude oil;
   - transportation of crude oil to refinement plant;
   - refinement of crude oil to produce gasoline;
   - distribution of gasoline to refueling stations.

   Table 1 summarizes the fuels in this study.

Vehicle technologies:

- PEM fuel cell powered 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.

3. Analysis and methodology

A full life cycle analysis of the vehicle should consider every step in the "vehicle cycle" and the "fuel cycle". The life cycle considers the total carbon dioxide emissions and the total energy consumption from every step. This methodology is similar to the methodology used in the previous study [7]. The "vehicle cycle" consists of five major steps:

- material production: the total emissions and energy consumption during the extraction and treatment of the raw material in order to produce the materials used in vehicles;
- assembly of vehicle: total emissions and energy consumption during the assembly of the vehicle from components in manufacturing plants;
- distribution of vehicle: total emissions and energy consumption during the distribution of vehicles from the assembly/manufacturing plant to dealers;
- maintenance of vehicle: total emissions and energy consumption to maintain the vehicle throughout the vehicle life time;
- disposal or recycling of vehicle: total emissions and energy consumption required to dispose of the vehicle at the end of vehicle lifetime.

The analysis of the "vehicle cycle" was carried out using published literature data [13,14] and GREET [15]. The necessary data for the analysis is the weight of the vehicle, the distribution of the material used in the vehicle by weight and the energy consumption and carbon dioxide emissions associated with each step. This data was used in a series of equations to obtain the results presented later in this paper. Our previous study provides the details of the analysis [7].

The energy used to vehicle material production was found from Schucker et al. [14], as shown in Table 2. 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 kg C GJ^{-1} [9] for both Canada and the United States. In the case of primary steel making, the emission factor used is 23.3 kg C GJ^{-1}[1] [13] (the average of coal and oil) for both Canada and the United States. For electricity supplied while producing the primary metal, the release of carbon was estimated using GREET to be 11.6 kg C GJ^{-1} [15] (Canada) and 19.9 kg C GJ^{-1} (United States) [15] 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 materials are summarized in Table 3.

Table 2
Breakdown of energy consumption in vehicle material production in Canada and the United States

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
Estimated Carbon Dioxide emissions per material [9]

Material	Material (kg C kg^{-1})	Material (kg CO_2 kg^{-1})
Glass	0.629	2.31
Magnesium	5.700	20.90
Copper	2.000	7.33
Zinc	1.000	3.67
Lead	0.900	3.30
Plastics	1.880	6.89
Rubber	1.463	5.36

The energy consumption during vehicle assembly 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} [14]. 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 for electricity are 11.6 kg C GJ^{-1} (Canada) [15] and 19.9 kg C GJ^{-1} (United States) [15] and 23.3 kg C GJ^{-1}[1] for oil for both situations [13].

The distribution energy is estimated by using an average transportation distance of 1600 km and an average energy consumption rate of 600 J kg^{-1} km^{-1}. The energy consumption for vehicle disposal at the end of vehicle lifetime is assumed to be 370 kJ kg^{-1} [14]. Since there is no available data on the emis-

[1] The carbon emission factor of oil was found from reference [13]. 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.

sions associated with energy consumption in the distribution and disposal steps and they are very small in comparison to the emissions of material production and vehicle assembly, they are neglected in this study. The emissions of distribution could be estimated as the emissions from the use of heavy duty trucks (i.e. burning gasoline in heavy duty trucks for a given amount of distance). Using GREET, the emissions associated with the distribution can be estimated as 32.06 kg of CO_2 in Canada and 34.3 kg of CO_2 in the United States.

The "fuel cycle" consists of the following steps:

- Feedstock
  - production: total emissions and energy consumption to extract raw materials;
  - transport: total emissions and energy consumption during the transportation of the raw materials to be treated.
- Fuel
  - production: total emissions and energy consumption during the production of the desired fuel (hydrogen or gasoline in this study);
  - distribution: total emissions and energy consumption while distributing the fuel to be used by consumers.
- Fuel use: total emissions and energy consumption due to the use of the fuel in vehicle.

The "fuel cycle" was analyzed using GREET 1.6 [15] (greenhouse gases regulated emissions and energy use in transportation). 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 emissions during the fuel use step are obtained from the carbon content in the fuel.

Table 4
Canadian and American electricity mix used in this study [12,13]

Energy source (%)	Canada	United States
Residual oil	2.4	2.9
Natural gas	5.5	17.8
Coal	18.8	49.9
Nuclear power	12.3	19.9
Others	61	9.6

The life of the vehicle assumed in this analysis is 300,000 km which is approximately 186,411 miles. It is important to specify the lifetime of the vehicle since the output given by GREET is on a per mile basis. Therefore, to obtain the total emissions and energy consumption for the "fuel cycle" the outputs were multiplied by the lifetime of the vehicle.

The major difference between Canada and the United States is the electricity mix as outlined in Table 4 [16,17]. Coal is used in very high quantities in the United States, while renewable and other energies are preferred in Canada. This difference in electricity mix will contribute to differences in energy consumption and emissions associated with the total life cycle of a vehicle. The electricity mix is very important to specify when using GREET. GREET uses the electricity mixes in its calculations. The electricity mix is needed to calculate the electricity usage of upstream fuel production activities. Also, the GREET model calculates the emissions associated with electricity generation from residual oil, natural gas, 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, known as others [15].

Finally, the well-to-tank efficiency was compared. The well-to-tank efficiency is obtained using GREET.

4. Limitations

The analysis discussed in this paper is based on published data from literature and on GREET and like any other analysis

Table 5
Weight distribution of present and future internal combustion engine vehicles (ICEV) and fuel cell vehicles (FCV) in Canada and the United States

Material	Present		Future	
	Gasoline ICEV, mass (kg)	Hydrogen FCV, mass (kg)	Gasoline ICEV, mass (kg)	Hydrogen FCV, 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

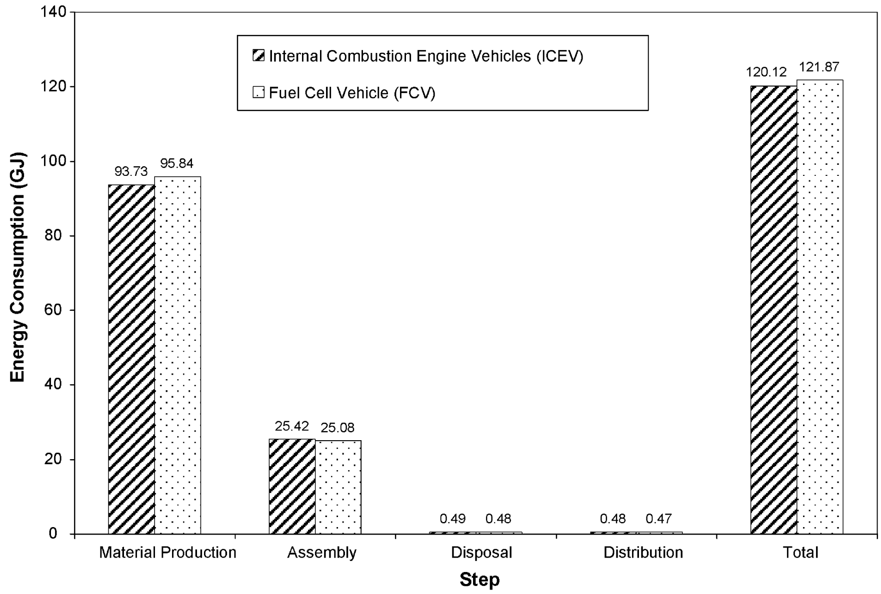

Fig. 1. Comparison of vehicle cycle energy consumption for present vehicles.

has 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. Results and discussion

5.1. Vehicle life cycle

As discussed earlier in the paper, the vehicle cycle consists of different steps that contribute to the total energy consumption and emissions. For the purpose of this study, the analysis carried out is mainly concerned with comparing the estimated energy consumption and carbon dioxide emissions in Canada and the United States. The material production step is very much dependent upon the average weight of each material being used in the vehicle. The remaining steps on the other hand are very much dependent upon the total weight of the vehicle itself. It

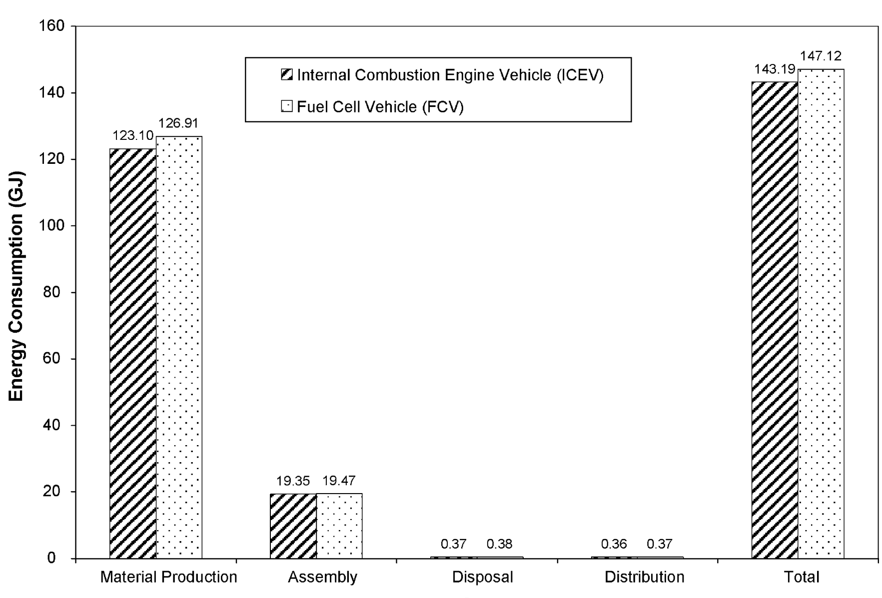

Fig. 2. Comparison of vehicle cycle energy consumption for future vehicles.

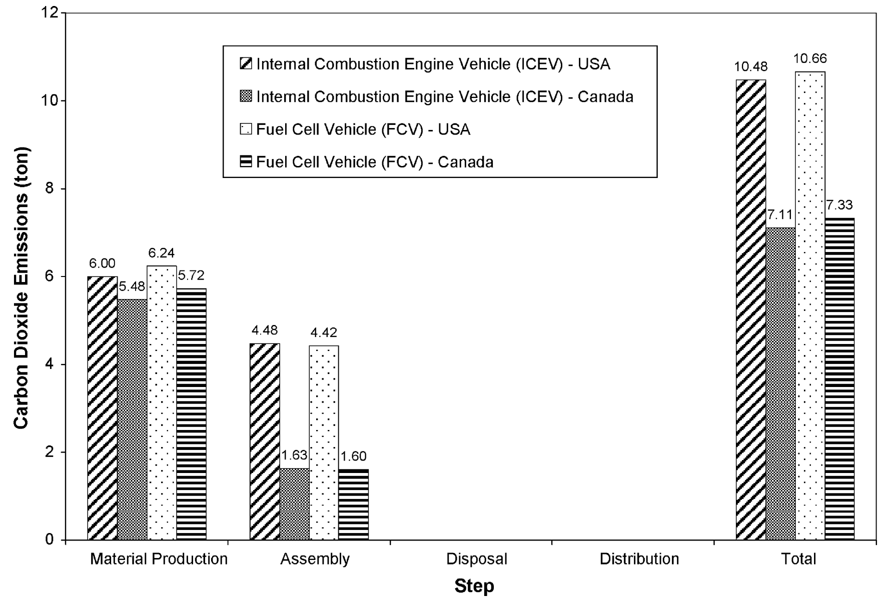

Fig. 3. Comparison of vehicle cycle carbon dioxide emissions for internal combustion engine vehicles (ICEV) and Fuel cell vehicles (FCV) in Canada and the United States for present vehicles.

is assumed that the average total weight of the vehicle and the distribution of the material in the vehicle is the same for Canada and the United sates vehicles as shown in Table 5. This is so since vehicles in both countries have to meet similar standards. In addition, automotive manufacturers are targeting the same demographic.

From the analysis, it is very clear that during the vehicle cycle, the material production step contributes most of the carbon dioxide emissions and consumes most of the energy in both Canada and the United States. For the present and future vehicles, it is responsible for almost 78 and 86%, respectively of the energy consumption, as illustrated in Figs. 1 and 2. The increase of aluminum use in the future vehicles results in the increase of energy consumption in both Canada and the United States. This portion of the study assumes that the energy consumption during the vehicle cycle is the same in Canada and the United States since the weight of the vehicle is the same in both situations.

Figs. 3 and 4 were constructed to compare the carbon dioxide emissions during the vehicle cycle in Canada and the United States for the present and future vehicles, respectively. It is clear that for the present vehicles, the total emissions of the vehicle cycle of an ICEV in the United States are 65.1% higher than those in Canada. Similarly, the total emissions of a FCV cycle in the United States are 64.6% higher those in Canada. For the future vehicles, the total emissions are 66.6% higher in the United States for an ICEV. Similarly, the total emissions of a FCV cycle

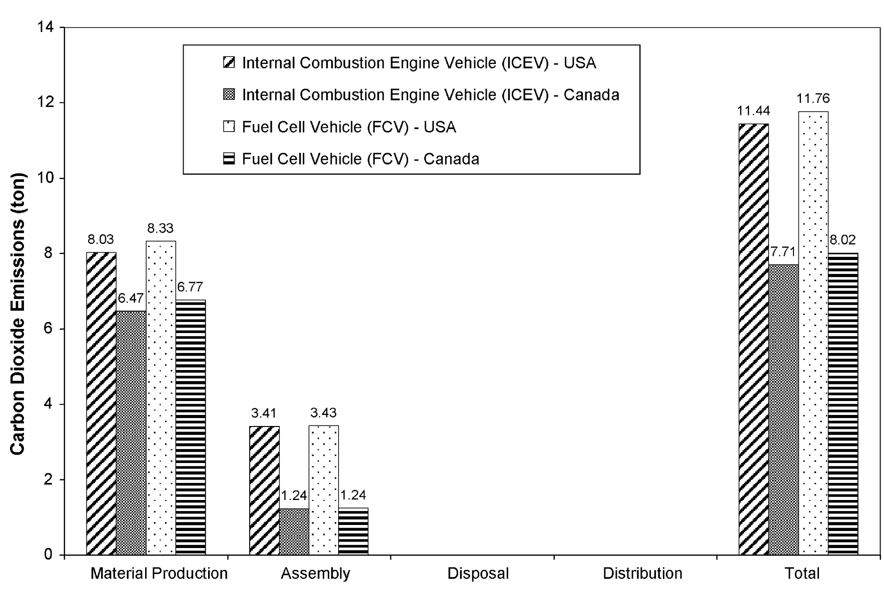

Fig. 4. Comparison of vehicle cycle carbon dioxide emissions for internal combustion engine vehicles (ICEV) and fuel cell vehicles (FCV) in Canada and the United States for Future vehicles.

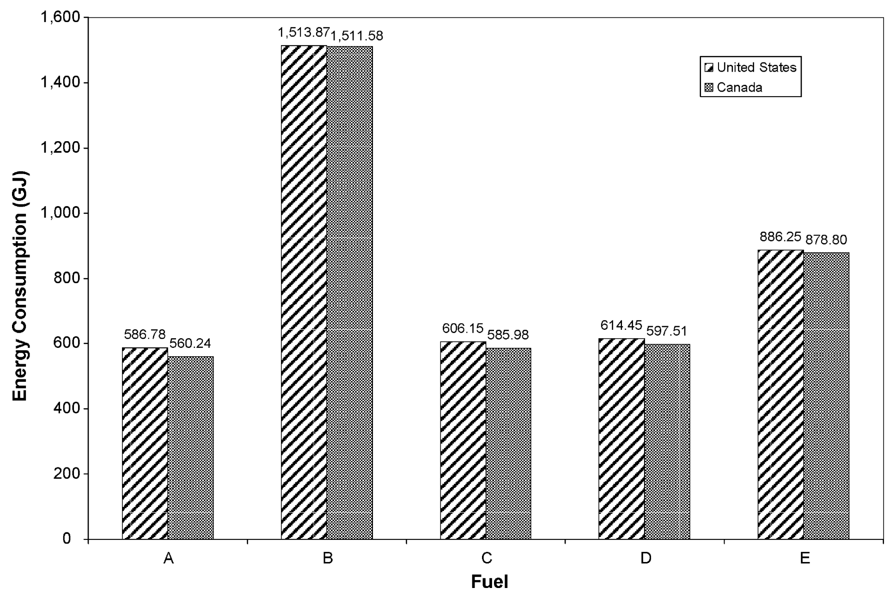

Fig. 5. Comparison of total energy consumption for the fuel cycle in Canada and the United States (for description of the fuels see Table 1).

in the United States are 66.7% higher than those in Canada under the future conditions. The total carbon dioxide emitted is much greater in the United States since the emission factor due to electricity use in Canada is lower than that in the United States (11.6 kg C GJ^{-1} versus 19.9 kg C GJ^{-1}).

5.2. Fuel life cycle

The analysis of the fuel life cycle has been conducted using GREET. GREET 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, processing and refinement, transporting and storing the fuel as well as consuming the fuel. One of the major differences between Canada and the United States is the electricity mix (basis of the comparison).

The analysis of the fuel life cycle of both situations, Canadian and American, conducted using GREET is shown in Figs. 5 and 6. These figures were created using the outputs of GREET in order to compare the energy consumption and the carbon dioxide emissions during the life cycle of hydrogen obtained by the four different methods and the life cycle of conventional gasoline for both situations. 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.

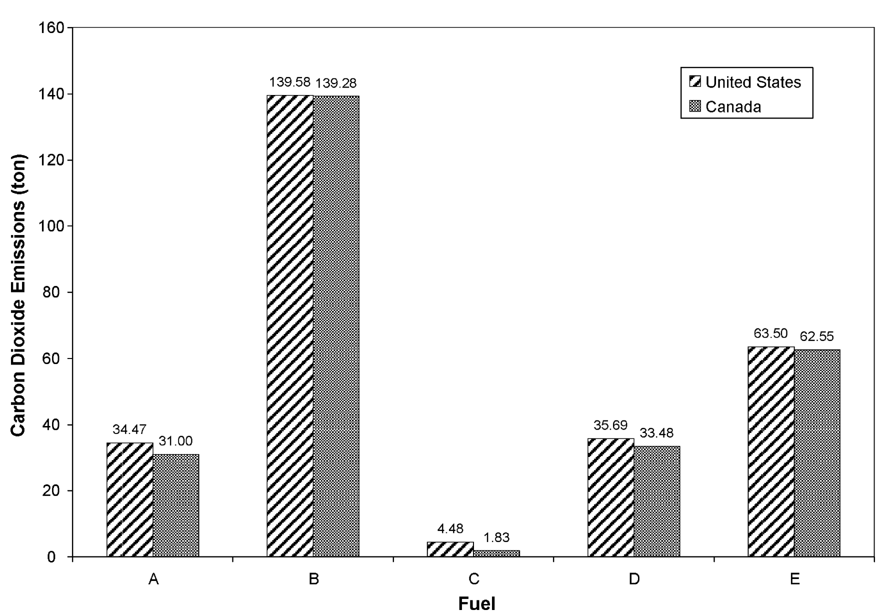

Fig. 6. Comparison of total carbon dioxide emissions for fuel cycle in Canada and the United States (for description of the fuels see Table 1).

Table 6
Comparison of conventional gasoline cycle between Canada and the United States—present

United States		Canada	
Total energy (fuel cycle) (GJ)	Total CO_2 (fuel cycle) (t)	Total energy (fuel cycle) (GJ)	Total CO_2 (fuel cycle) (t)
1259.30	90.23	1247.93	88.83

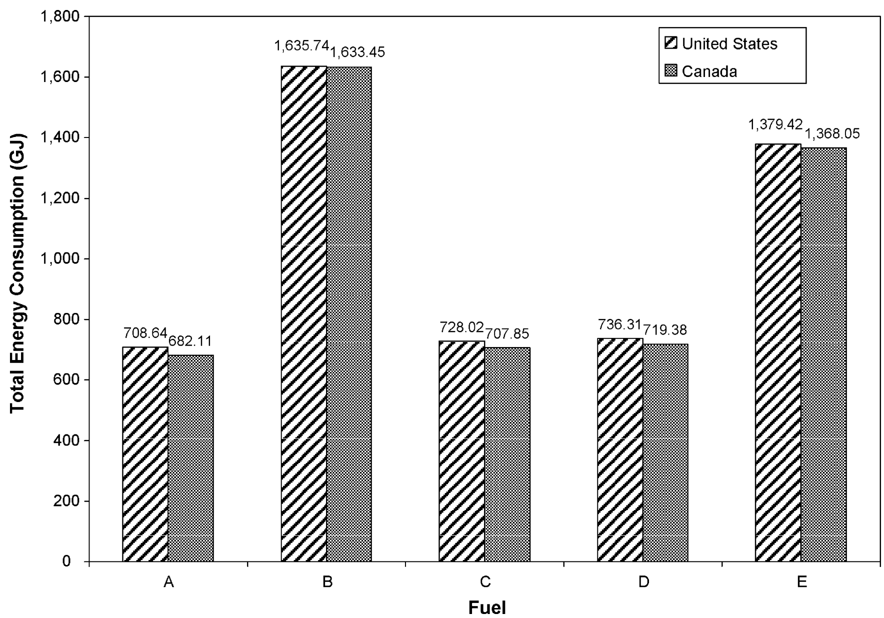

Fig. 7. Comparison of total life cycle energy consumption in Canada and the United States for the present vehicles (for description of the fuels see Table 1).

As illustrated, the energy consumption and the carbon dioxide emissions are higher in the United States than in Canada. Again this is due to the fact that more coal is used in the American electricity generation and more renewable energy is used in the Canadian electricity production. The extraction of hydrogen via steam reforming of natural gas in a natural gas power plant leads to the largest differences between the two situations. It is obvious that in Canada 26.54 GJ of energy and 3.47 t of carbon dioxide are saved per vehicle. In addition, a decrease of 16.93 GJ of energy and 2.21 t of carbon dioxide when hydrogen is extracted via steam reforming of natural gas in the hydrogen refueling station is seen in Canada. Further, extracting hydro-

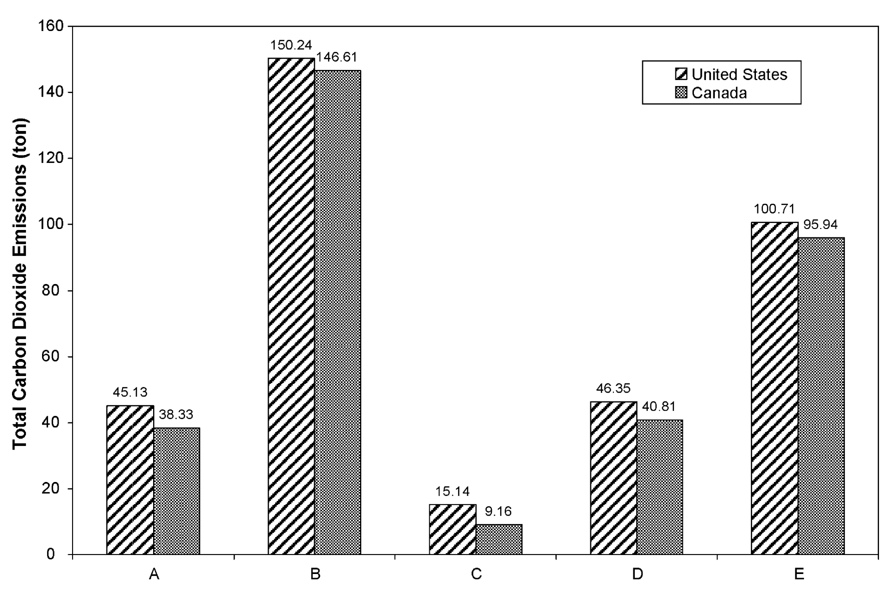

Fig. 8. Comparison of total life cycle carbon dioxide emissions in Canada and the United State for the present vehicles (for description of the fuels see Table 1).

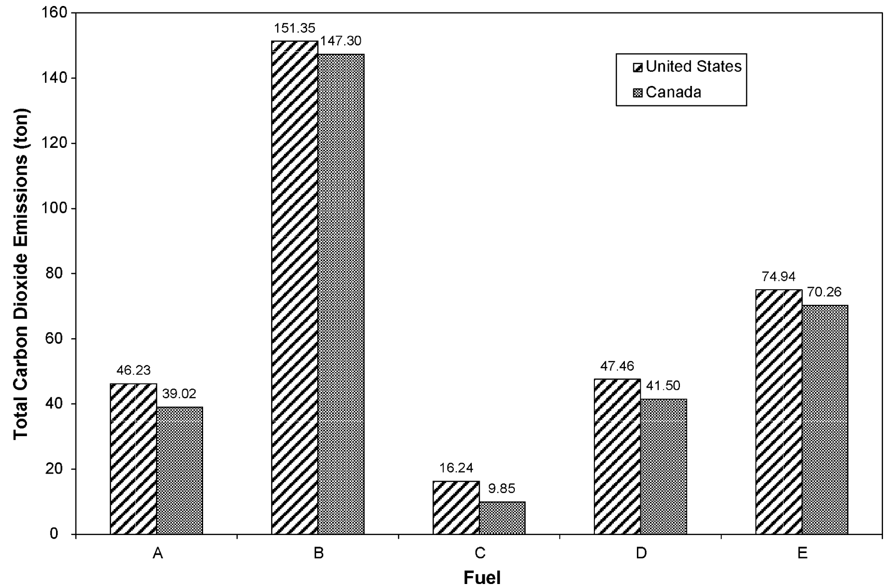

Fig. 9. Comparison of total life cycle carbon dioxide emissions in Canada and the United States for the future vehicles (for description of the fuels see Table 1).

gen from the use of electricity via nuclear power leads to a difference of 20.17 GJ of energy and 2.65 t of carbon dioxide between Canada and the United States; the GHG emissions and energy consumption in Canada are lower. Moreover, the lowest difference in energy use and emissions between the two countries (2.28 GJ of energy and 0.3 t of carbon dioxide emissions) is seen when hydrogen is extracted via electricity from coal. The energy use and emissions in the United States are higher. Finally, total energy consumption of conventional gasoline life is 7.46 GJ lower in Canada and the emissions are 0.95 t lower in Canada.

The above result was obtained for the future condition. The difference between the present and future condition in this case is the conventional gasoline. The energy and emissions are lower under the long-term conditions in both countries. 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 miles per gallon and the present is assumed to travel 22.4 miles per gallon [15]. The present conventional gasoline life cycle in Canada and the United States is shown in Table 6. The present and future conditions are used later in this paper to analyze the total life cycle of FCV and ICEV.

5.3. Total life cycle of an ICEV and an FCV

The “Total Life Cycle” of an ICEV and FCV is basically the sum of the “Fuel Life Cycle” and “Vehicle Life Cycle”. This study is carried out in order to compare the total life cycle of

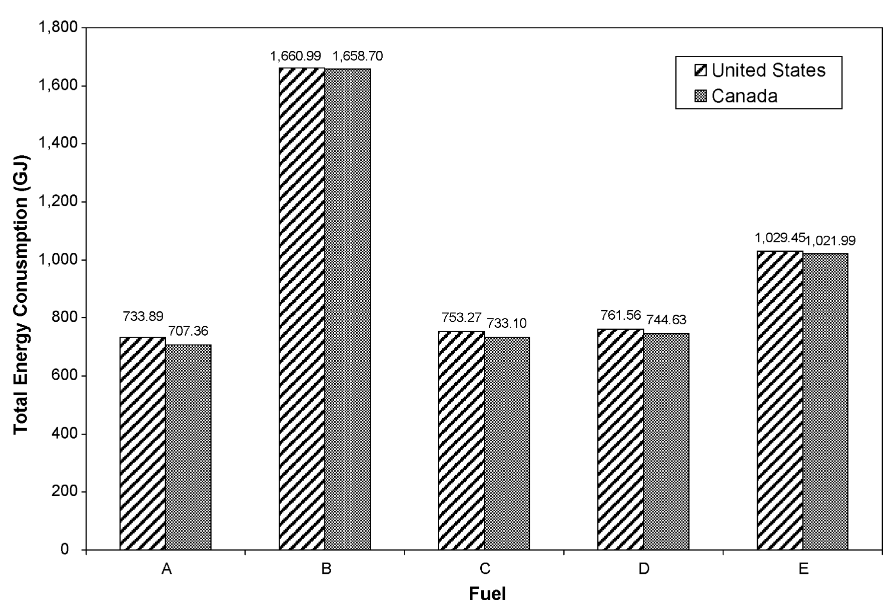

Fig. 10. Comparison of total life cycle energy consumption in Canada and the United States for the future vehicles (for description of the fuels see Table 1).

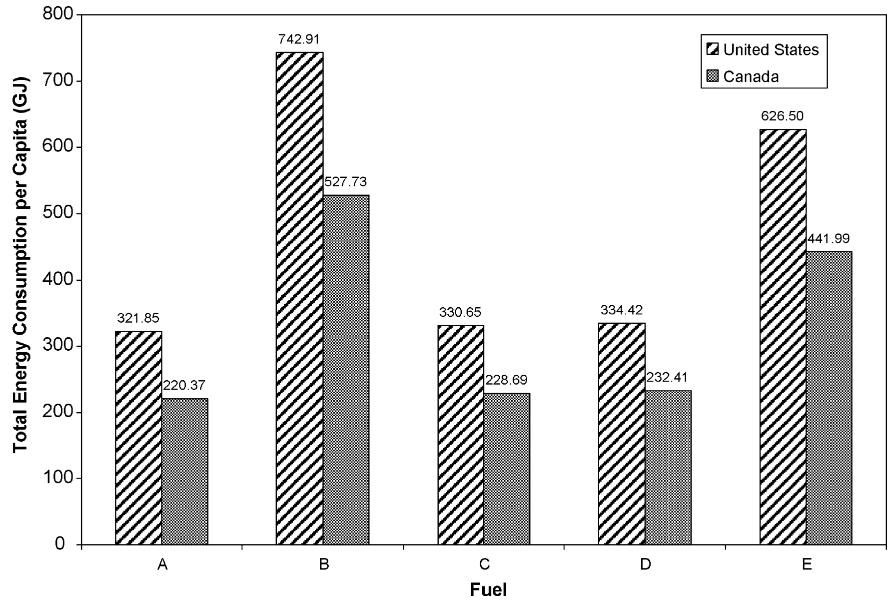

Fig. 11. Comparison of total life cycle energy consumption per capita in Canada and the United States for the present vehicles (for description of the fuels see Table 1).

the vehicles in Canada and the United States and under two conditions (present and future).

5.3.1. Present conditions

Under this condition, the present vehicle weight and material distribution are considered. The analysis done is summarized in Figs. 7 and 8. It is apparent, that the energy consumption and carbon dioxide emissions trends are the same for Canada and the United States. 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. Also, as expected, using the method of electrolysis from coal to extract hydrogen in both countries will lead to the highest emissions and energy consumption.

The analysis of the total life cycle of the vehicles put forward shows that the difference in energy consumption between the two situations depends solely on the fuel cycle. This is true since the energy consumption of the vehicles in Canada and the United States is shown to be the same. It is assumed that the total vehicle weight in both countries is the same.

In addition, the total life cycle is higher in the United States than that in Canada. It is apparent that using the Canadian electricity mix will save up to 26.54 GJ of energy and 6.80 t of CO_2 on a per vehicle basis. This is accomplished when hydro-

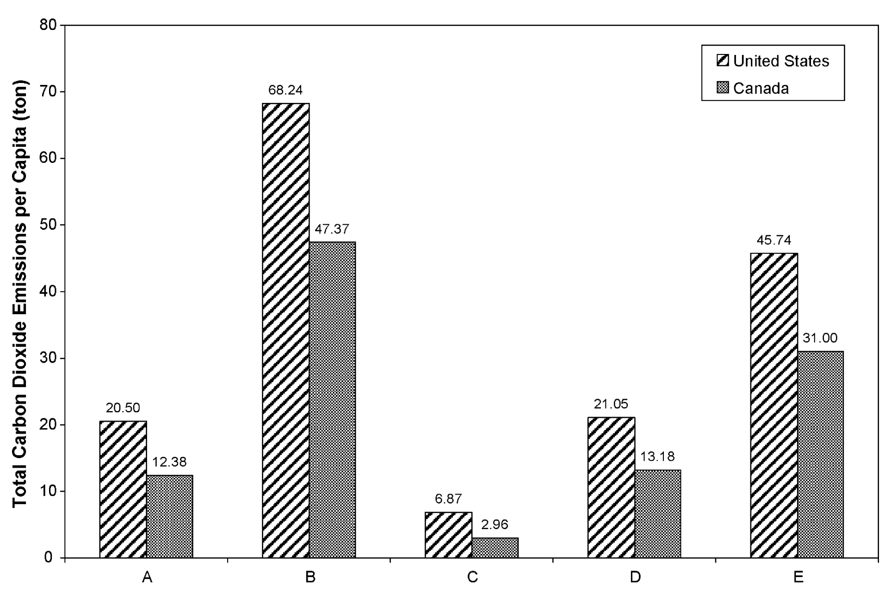

Fig. 12. Comparison of total life cycle carbon dioxide emissions per capita in Canada and the United States for the present vehicles (for description of the fuels see Table 1).

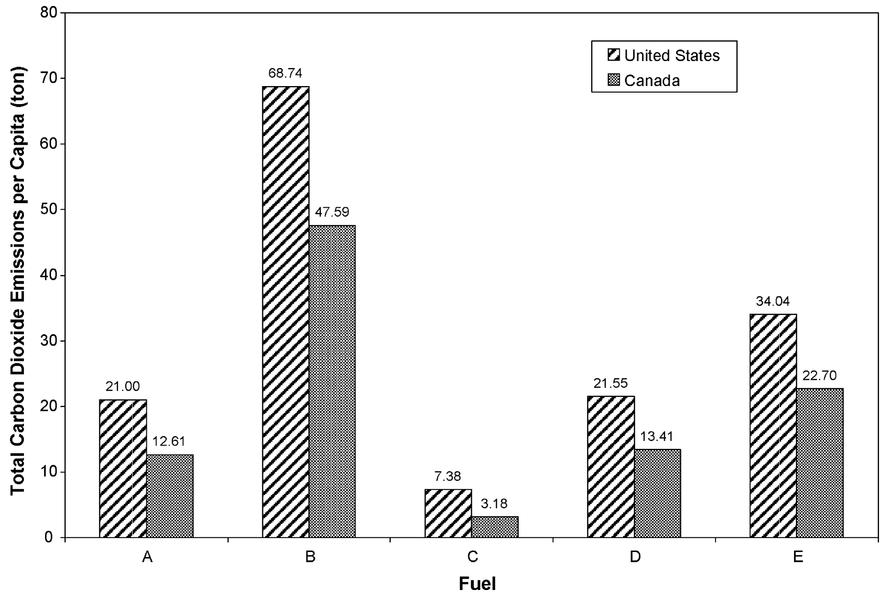

Fig. 13. Comparison of total life cycle carbon dioxide emissions per capita in Canada and the United States for the future vehicles (for description of the fuels see Table 1).

gen is extracted via steam reforming NG in a NG power plant. When hydrogen is extracted via electrolysis from coal the total energy consumption in Canada is 2.28 GJ less than in the United States and the total CO_2 emissions are 3.63 t less than the United States. When hydrogen is extracted from steam reforming NG in the hydrogen refueling station the total energy consumption is 16.93 GJ less in Canada than the United States and the total CO_2 emissions are 5.54 t less in Canada. Similarly, if hydrogen is extracted via electrolysis from nuclear power, the total energy used is 20.17 GJ less in Canada than the United States and the total CO_2 emissions are 5.98 t less in Canada. Finally, in the case of conventional gasoline, the total energy used is 11.37 GJ less in Canada and the total CO_2 emissions are 4.77 t less in Canada.

5.3.2. Future conditions

Under this condition, the future vehicle weight and material distribution are considered. The results are shown in Figs. 9 and 10. It is again apparent, that the energy consumption and carbon dioxide emissions trend is the same in Canada and the United States. The emissions are lower for the FCV.

Similar to the present condition, here the total life cycle of the vehicles depends solely on the fuel cycle since it is assumed that the total vehicle weight for both countries is the same.

In addition, it is clear that the total life cycle is higher in the United States than that in Canada. It is seen that using the Canadian electricity mix will save up to 26.54 GJ of energy and 7.22 t of CO_2 on a per vehicle basis. This is accomplished when hydrogen is extracted via steam reforming NG in a NG power

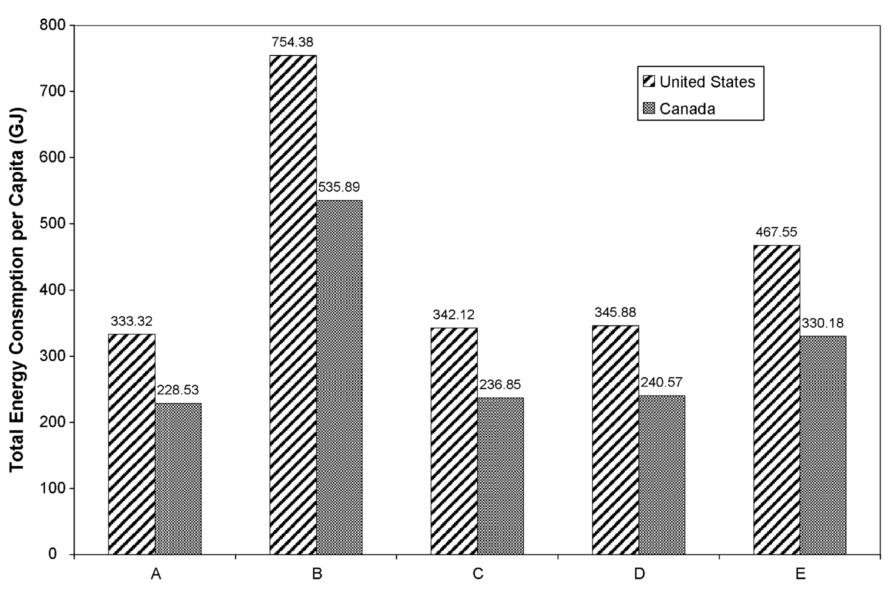

Fig. 14. Comparison of total life cycle energy consumption per capita in Canada and the United States for the future vehicles (for description of the fuels see Table 1).

plant. When hydrogen is extracted via electrolysis from coal the total energy consumption in Canada is 2.28 GJ less than in the US and the total CO_2 emissions are 4.05 t less than the US. When hydrogen is extracted from steam reforming NG in the hydrogen refueling station the total energy consumption is 16.93 GJ less in Canada than the US and the total CO_2 emissions are 5.95 t less in Canada. Similarly, if hydrogen is extracted via electrolysis from nuclear power, the total energy used is 20.17 GJ less in Canada than the US and the total CO_2 emissions are 6.39 t less in Canada. Finally, in the case of conventional gasoline, the total energy used is 7.46 GJ less in Canada and the total CO_2 emissions are 4.68 t less in Canada.

Therefore, it can be concluded that under both the present and future conditions, the use of hydrocarbons and other renewable energies in the electricity mix will result in lower energy consumption and carbon dioxide emissions.

In order to better comprehend the extent of the difference between Canada and the United States, let us consider the total passenger vehicles driven on the roads of Canada and the United States. In Canada, it is estimated that the total passenger vehicles on the road are 10.5 million [18] and in the United States the total is 134.3 million [19]. In addition, the population of both countries should be taken into account to find the difference on a per capita basis. The population of Canada is 32.8 million and of the United States is 295.7 million [20]. The comparison of total emissions and energy consumption on a per capita basis is shown in Figs. 11–14. Under the present conditions, this comparison yields a difference on a per capita basis of 101.48 GJ and 8.11 t of carbon dioxide when hydrogen is extracted from steam reforming NG in a NG plant; Canada has lower energy consumption and carbon dioxide emissions. When hydrogen is extracted via electrolysis from coal, the energy consumption and carbon dioxide emissions are decreased by 215.18 GJ and 20.87 t per capita respectively using the Canadian electricity mix. In addition, the Canadian electricity mix will save up to 101.96 GJ of energy and 3.92 t of carbon dioxide on a per capita basis when hydrogen is extracted via electrolysis from nuclear power. When hydrogen is obtained from steam reforming NG in a hydrogen refueling station, 102 GJ of energy and 7.87 t of carbon dioxide per capita are saved in Canada. Finally, in the case of conventional gasoline, the total energy used is 184.51 GJ less in Canada and the total carbon dioxide emissions are 14.74 less in Canada on a per capita basis.

Similarly, for future vehicles, the Canadian electricity mix will save up to 104.79 GJ of energy and 8.39 t of CO_2 per capita when hydrogen is extracted via steam reforming NG in a NG power plant. When hydrogen is obtained via electrolysis from coal, the difference on a per capita basis is 218.49 GJ of energy and 21.15 t of CO_2, Canada having the lower energy consumption and emissions. When hydrogen is extracted from steam reforming NG in a hydrogen refueling station, the total energy consumption is 105.31 GJ less in Canada and the total CO_2 emissions are 8.15 t less in Canada. Similarly, extracting hydrogen via electrolysis from nuclear power will result in a saving of 105.27 GJ of energy and 4.19 t of CO_2 per capita using the Canadian electricity mix. Finally, for conventional gasoline the savings per capita are 137.37 GJ of energy and 11.34 t of CO_2 in Canada.

5.4. Well-to-tank efficiency

A comparison between the well-to-tank efficiency of the vehicles in Canada and the United States is carried out in this study. The well-to-tank efficiency is 1 BTU of energy over the energy consumption during the fuel cycle needed to obtain that 1 BTU of energy. Therefore, the well-to-tank efficiency depends largely on the method of obtaining the fuel.

A comparison of the well-to-tank efficiency between the two countries is shown in Fig. 15. As illustrated, the well-to-tank efficiency in Canada is higher than that in the United States.

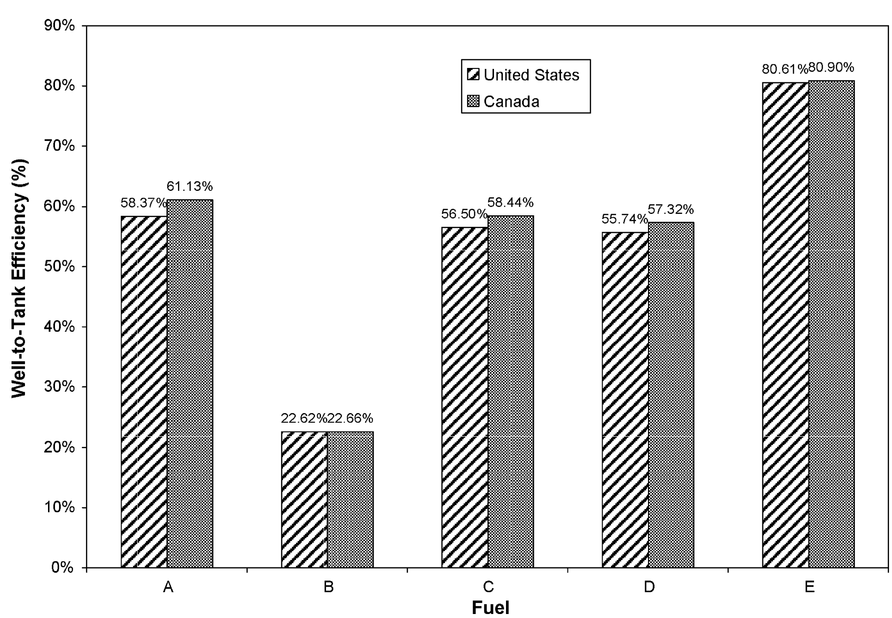

Fig. 15. Comparison of well-to-tank efficiency in Canada and the United States (for description of the fuels see Table 1).

This is true since as discussed earlier the energy consumption during the life cycle of the fuel using the American electricity mix is higher than that using the Canadian electricity mix. In addition, it is obvious that the well-to-tank efficiency in both countries while obtaining hydrogen via electrolysis from coal is very close. Likewise, the efficiency in both countries of obtaining conventional gasoline is almost the same.

6. 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 energy realities in Canada and the United States, 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 in Canada and the United States.

Using the Canadian electricity mix will result in lower carbon dioxide emissions and energy consumption than using the American electricity mix because of more electricity from renewable (or non-carbon based) primary energy sources. For the present vehicles, using the Canadian electricity mix will save up to 215.18 GJ of energy and 20.87 t of CO_2 on a per capita basis and 26.53 GJ of energy and 6.8 t of CO_2 on a per vehicle basis. Similarly, for the future vehicles, using the Canadian electricity mix will lower the total carbon dioxide emissions by 21.15 t and the energy consumed is reduced by 218.49 GJ on a per capita basis and 26.53 GJ of energy and 7.22 t of CO_2 on a per vehicle basis.

Finally, the well-to-tank efficiencies are higher when using the Canadian electricity mix. This is so since the energy consumption for the fuel cycle is lower than that in the United States. Similar trends are seen in both situations. The most efficient method of obtaining hydrogen in both situations is via steam reforming of NG in a NG power plant.

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