Evaluating the Energy Consumption and Emissions of Direct Alcohol Fuel Cells

Lin Gao[*1], Malintha C. Abeysiri[2], Zach C. Winfield[3]

Department of Chemistry, Environmental Science, and Geology, University of Mary Hardin-Baylor
900 College Street, Belton, Texas 76513, USA

[*1]lgao@umhb.edu; [2]mabeysiri@mail.umhb.edu; [3]zcwinfield@mail.umhb.edu

Abstract- **As a result of recent developments in fuel cell technology, serious consideration is given to direct alcohol fuel cells in which alcohol is used directly as the fuel. Methanol and ethanol are the most promising fuels for transportation applications. To assess the environmental benefits of these fuel choices over petroleum, it is important to analyze their energy uses and emissions during the entire fuel cycle. A direct alcohol fuel cell model was developed with a software simulation, and a data analysis was conducted based on the simulation results. Energy consumption and emissions were calculated throughout the entire cycle from well-to-wheels (WTW). It was observed that the direct methanol fuel cell (DMFC) reduces energy consumption and emissions, and that when ethanol, a renewable energy source, is used in fuel cells, it will significantly cut emissions from fuel cells. However, ethanol uses more energy throughout the entire cycle.**

Keywords- Well-to-wheels; Direct Methanol Fuel Cell; Direct Ethanol Fuel Cell; Fuel Efficiency; Greenhouse Gas

I. INTRODUCTION

Considerable alternative energy source research to supplement oil as the main energy source for road vehicle energy has resulted from the growing demand for transportation fuels, the rising public concerns for environmental problems, and the increasing use of existing fossil fuels. In recent years, fuel cells have attracted interest due to their low degree of pollution, high efficiency, and capability to use alternative and renewable fuels. Hydrogen is the most commonly used fuel in proton exchange membrane fuel cells (PEMFC). Direct alcohol/air PEMFC is a developing technology and is promising for application in electric vehicles. Among the different alcohols, methanol and ethanol are the most promising because of their advantages in comparison to hydrogen. These advantages include high aqueous electrolyte solubility, low liquid fuel cost, easy handling, easy transportation and storage, and high energy density [1,2].

A few research groups have demonstrated the use of direct alcohol fuel cells in electric vehicles [3-5]. In addition, the energy conversion efficiencies in direct alcohol fuel cells have been studied by using various electrolyte membranes [6, 7]. However, previous research has focused on vehicle operation stage. Although alternative fuels tend to generate lower emissions and achieve higher fuel efficiencies than conventional fuels, it is necessary to analyze the energy use and the emissions during the entire well-to-wheels (WTW) fuel cycle. However, a WTW analysis of using alcohol as a fuel was not found in the literature. In this paper, we present a detailed WTW analysis of alternative fuel (such as ethanol and methanol) energy efficiencies and emissions to understand their environmental advantages. This study provides an objective efficiency and emission comparison among the selected fuels and attempts to discover the most effective method for alternative fuel use.

II. METHODOLOGY

A. Principles of Direct Alcohol Fuel Cells

A fuel cell is an energy conversion device that converts chemical energy into electricity by a chemical reaction between oxygen and a fuel. Hydrogen is the most common fuel. The hydrogen reactions involved in the anode and cathode are given in Equations (1) and (2).

$$\text{Anode:}\quad H_2 \rightarrow 2H^+ + 2e^- \qquad (1)$$

$$\text{Cathode:}\quad (1/2)O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad (2)$$

Due to the safety concerns and storage and distribution difficulties associated with hydrogen, other hydrocarbon fuels, such as alcohols (i.e., methanol and ethanol), are studied as fuel cell alternatives. Methanol and ethanol overcome the storage and infrastructure challenges of hydrogen use. In vehicle applications, hydrogen is typically reformed on-board before being fed into fuel cells. However, this method results in an energy loss. Furthermore, high temperatures are required during the reforming process. Direct methanol fuel cells (DMFCs) and direct ethanol fuel cells (DEFCs) directly convert liquid methanol and ethanol into electric energy without reforming. To create power in a DMFC or DEFC, a mixture of water and methanol or ethanol is introduced into the fuel cell. Methanol is converted into carbon dioxide at the anode and water is formed at the cathode by using the oxygen from air. These reactions are shown in Equations (3) and (4).

$$\text{Anode:}\quad CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \qquad (3)$$

$$\text{Cathode:}\quad (3/2)O_2 + 6e^- + 6H^+ \rightarrow 3H_2O \qquad (4)$$

The direct electrochemical oxidation of ethanol occurs at the anode and the electroreduction of oxygen occurs at the cathode as shown in Equations (5) and (6), respectively.

$$\text{Anode:}\quad C_2H_5OH + 3H_2O \rightarrow 2CO_2 + 12H^+ + 12e^- \qquad (5)$$

$$\text{Cathode:}\quad 3O_2 + 12H^+ + 12e^- \rightarrow 6H_2O \qquad (6)$$

B. Efficiency of Fuel Cells

Currently, one technology deficiency of these fuel cells is that some methanol or ethanol passes through the polymer membrane without producing electricity during the chemical reactions. This phenomenon is referred to as methanol or ethanol permeation (cross-over). Thus, the DMFC and DEFC efficiencies are generally lower than those of hydrogen PEMFCs [8].

The theoretical open circuit voltages (E_0) can be calculated by dividing the Gibbs free energy of reaction (ΔG) by the number (n) of electrons transferred during the reaction and the Faraday constant (F) (Equation 7).

$$E_0 = \frac{\Delta G}{n \times F} \tag{7}$$

This reaction results in a voltage (E_0) of 1.21 V for methanol and 1.145 V for ethanol [1].

During normal operation, the cell potential tends towards lower voltages. This tendency is caused by ohmic losses, over voltages at the electrodes and the formation of a mixed potential at the cathode [9]. At 0.5 V and 97% fuel utilization, the overall conversion efficiencies of methanol and ethanol to electricity are approximately 40% and 42%, respectively.

When a DMFC or a DEFC is used for transportation applications, it needs auxiliary components to ensure that the stack works in its optimal condition. In addition to the stack, the system consists of at least a fuel tank, a heat exchanger, a pump, a compressor, sensors and actuators. The energy loss in the system is a combination of the fuel cell energy use and the auxiliary energy consumption. Accordingly, the system efficiency is lower than the fuel cell conversion efficiency. Direct alcohol fuel cell efficiency information from vehicles has not been determined previously. A stand-alone DMFC study showed that the system efficiency ranged from between 25% and 30% and had a fuel utilization of 90% [9]. The current density and cell potential characteristics of a DEFC are similar to the density of a DMFC [1]. Thus, for simplicity, we assumed that the efficiency of an ethanol fuel cell was similar to the efficiency of a DMFC.

C. *Well-to-Wheels Simulation*

The well-to-wheels analysis is a systematic approach for assessing the energy consumption and greenhouse gas (GHG) emissions from different fuels and vehicle propulsion configurations. The entire WTW cycle is comprised of two independent stages that are shown in Fig. 1. These stages consist of a well-to-pump (WTP) stage (I) and a pump-to-wheels (PTW) stage (II). Stage I includes the recovery or production of the feedstock for the fuel, the transportation and storage of the energy source through feedstock conversion to fuel and the subsequent fuel transportation, storage, and distribution to the vehicle. Stage II refers to the vehicle operation activities throughout its lifetime [10]. The GREET software was used to study the full energy cycle, energy use and the GHG emissions. This software consists of multidimensional worksheets that were developed to address analytical issues associated with various fuels.

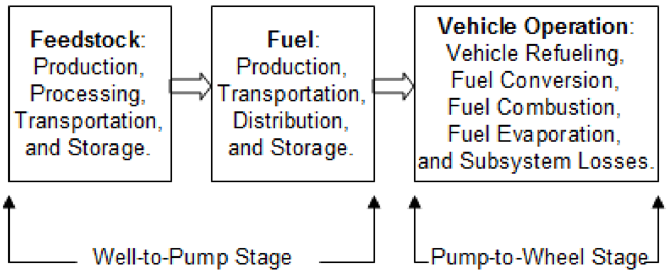

Fig. 1 Energy cycle stages used in this analysis

III. RESULTS AND DISCUSSION

As an alternative to fossil fuels, methanol and ethanol have been widely used in transportation since the invention of the internal combustion engine (ICE). When mixed with gasoline, methanol and ethanol can be used in combustion engines as high-level blended fuels. In the U.S., M90 and E85 refer to 90% methanol and 85% ethanol blends, respectively. Another exciting application of alcohol is its use in fuel cells. There are two different types of alcohol fuel cells in use, the hydrogen fuel cell with reformers or the DMFC/DEFC. Fig. 2 shows the alcohol fuels that are used for transportation.

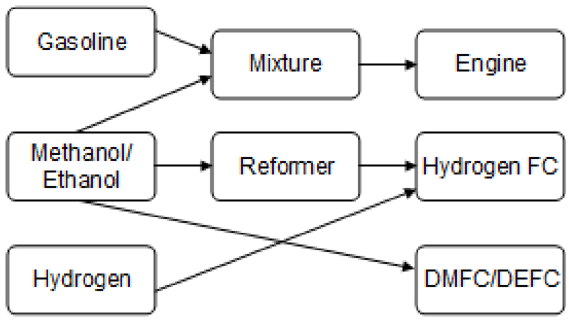

Fig. 2 Alcohol fuels used for transportation

In this study, alcohol fuels that are used in different energy conversion devices were simulated to evaluate the full cycle energy consumption and GHG emissions. For comparison, a conventional gasoline vehicle and a hydrogen fuel cell were simulated. A summary of the simulations is presented below.

- Conventional vehicle (CONV) with gasoline engine (SI)
- ICE vehicle (ICEV) using a 90% methanol and 10% gasoline (M90) mixture
- Hydrogen fuel cell vehicle (H2FCV) with an on-board liquid methanol (LM) reformer
- Vehicle powered by a direct methanol fuel cell (DMFC)
- ICEV using a 85% methanol and 15% gasoline (E85) mixture
- Hydrogen fuel cell vehicle with an on-board liquid ethanol (LE) reformer
- Vehicle powered by a direct ethanol fuel cell (DEFC)
- Gaseous hydrogen fuel vehicle (H2FCV)

A. *Fuel Economy in the PTW Stage*

The PTW vehicle economy is defined as the distance travelled per unit volume of fuel used (in kilometers per liter (km/l) or in miles per gallon (mpg)). Passenger vehicles account for over 60% of vehicles worldwide. Thus, a conventional medium size passenger car that uses gasoline was selected as the baseline vehicle. The fuel economy was based on a combination of the urban and highway fuel economies, with 55% urban driving and 45% highway.

A direct alcohol fuel cell model was developed in the GREET software. The fuel economies and GHG emissions of the DMFC and DEFC vehicles were modelled on the basis of the hydrogen fuel cell vehicle models. The FCV uses an electric motor and rechargeable batteries to drive the system. The hydrogen FCV and DMFC/DEFC vehicles were assumed to have the same configuration and component efficiencies (for example, motor, batteries, gears, vehicles, etc.) except for the fuel cells. Accordingly, the vehicle fuel to wheel efficiency is proportional to the fuel cell efficiency. The theoretical energy efficiency from hydrogen to electricity of fuel cells is up to 83%. In fact, the hydrogen fuel cell efficiencies are approximately 55%, and range between 50% and 65% if the peripheral system efficiencies (for example, the air and cooling systems) are considered. The overall vehicle efficiency (excluding fuel cells) was assumed to be approximately 82%. Thus, the fuel to wheel efficiencies are between 41% and 54% and have a mean value of 45% [11, 12]. The DMFC and DEFC efficiencies are estimated to be 35% in the simulation. Thus, the entire fuel to wheel efficiency is approximately 29%, which results in a fuel economy of 15.7 km/l. The DMFC and DEFC vehicle efficiency estimates are summarized in Table I. Fig. 3 illustrates a comparison between the average fuel economies of vehicles that use different technologies.

TABLE I DMFC AND DEFC FUEL ECONOMY ESTIMATIONS

Fuel Type	Hydrogen	DMFC / DEFC
Fuel cell efficiency (%)	55	35
Other system efficiency (%)	82	82
Fuel to wheel efficiency (%)	45	29
PTW Fuel economy (km/l)	**24.6**	**15.7**

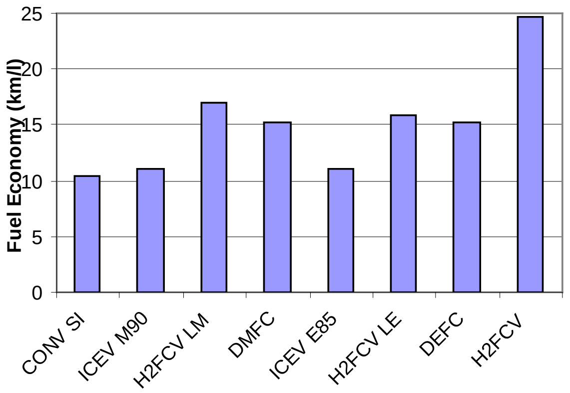

Fig. 3 Fuel economy comparisons (km/l) in the PTW stage

A. *Energy Efficiency in the WTP Stage*

These efficiencies were calculated from the energy losses that occur along the pathway from the primary energy feedstocks to the fuels that are available from the fuel pumps at refuelling stations. The crude-to-gasoline pathway has a high efficiency of 82.6%. The efficiency of crude oil recovery is approximately 98%, and the efficiency of gasoline refinement is only 89%.

Methanol can be produced from a wide variety of sources, including fossil fuels, such as natural gas, coal and oil shale. However, methanol can also be produced from agricultural products and municipal wastes, such as wood and various types of biomass. Fossil fuels are the main sources for making hydrogen from water and can be used to produce hydrogen by electrolysis and thermolysis methods. Currently, for large quantities of industry applications, hydrogen and methanol are produced by natural gas steam reforming. Natural gas recovery and processing are 97% efficient. However, reforming is an inefficient method that results in energy losses of more than 30%. Furthermore, hydrogen must be compressed to be more energy dense for transportation. This compression results in an additional energy loss of 10% [13]. Combined, these factors result in low hydrogen WTP efficiency. One major advantage of methanol over hydrogen is that methanol is easy to transport. Methanol is a high energy-dense liquid under normal conditions, which allows it to be easily stored, transported and dispensed (much like gasoline).

Ethanol made from corn is classified as a renewable energy source. Ethanol is produced from biomass through industrial fermentation, chemical processing and distillation. Corn is the main feedstock used for ethanol production in the U.S. This ethanol is mainly used in blends of ethanol and gasoline for automotive engines. Unlike other natural fuel resources (such as petroleum and natural gas) that already exist in the earth, corn is grown specifically for the production of ethanol fuel. Corn farming and the production of ethanol fuel are relatively energy intensive processes that require the use of non-renewable energy. The efficiency during the feedstock stage is normally less than 50%. Furthermore, ethanol cannot be transported in pipelines because it absorbs water from the inside of pipelines. Ethanol must be delivered by truck, which is the least energy-efficient transportation method for liquids. Therefore, the energy efficiency of ethanol in the WTP stage is less than 40%, which is much lower than the efficiency of other fuel pathways. Fig. 4 shows the WTP efficiencies of the different fuels. Here, it is assumed that the ethanol WTP efficiency for the DEFC is the same as that of the ethanol used in the hydrogen reformer fuel cells. A similar assumption is made for methanol. Specifically, it is assumed that the WTP efficiency of a DMFC vehicle equals that of a methanol-using hydrogen reformer FCV.

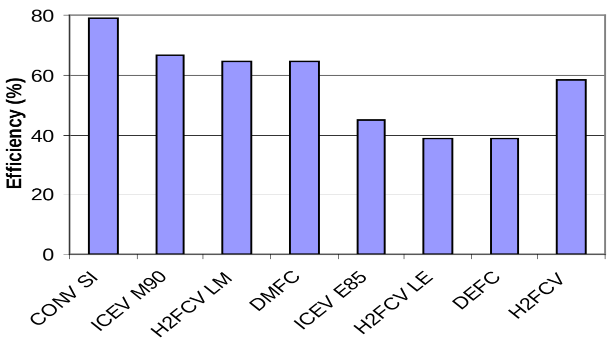

Fig. 4 WTP efficiency comparisons

B. WTW Energy Consumption and GHG Emissions

As previously determined, some fuels have higher fuel economies in the PTW stage and others use less energy in the WTP stage. The simulated energy uses of the different technologies throughout the entire WTW cycle and their quantities during each stage are shown in Fig. 5. Vehicles that use E85 consume the most energy, while hydrogen FCVs use the least. A DMFC vehicle uses less energy than a conventional vehicle due to its higher PTW efficiency. However, these vehicles cannot compete with the hydrogen FCV because of the high energy efficiency of the hydrogen fuel cell. For those using the same fuel (for example, methanol or ethanol), the vehicles powered by fuel cells use significantly less energy than those with combustion engines. Thus, the development of fuel cell technologies is important.

It was previously assumed that the DMFC/DEFC fuel usage is higher than that of a hydrogen fuel cell and a methanol/ethanol reformer combination. More energy is used in the WTP stage to process, transport and distribute the fuels. Thus, the direct fuel cell energy consumption during the entire fuel cycle is higher than that of a reformer-based fuel cell, although the difference between them is trivial. However, there are several disadvantages of reforming fuel to create hydrogen for fuel cells. Onboard reformers increase the complexity, cost, packaging and maintenance demands of a fuel cell system. The carbon monoxide produced during the reforming process can damage the fuel cell performance if it reaches the fuel cell anode [14].

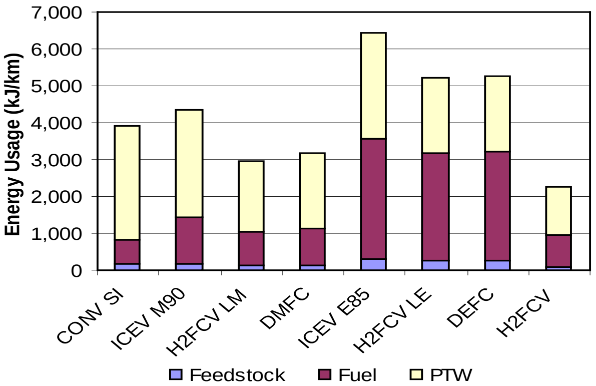

Fig. 5 Various vehicle energy usages in each fuel stage

Ethanol fuels, including the DEFC, use a considerable amount of energy in the entire fuel cycle because of the energy that is required to grow, gather, process and transform the corn to ethanol. For ethanol, the energy consumed in the WTP stage accounts for more than 50% of the total energy usage (Fig. 5). The amount of energy use in only the vehicle cycle (>3000 kJ/km) is close to or higher than the entire energy use of the other vehicles in the WTW cycle. However, methanol and hydrogen are made from natural gas, which is a fossil fuel, while ethanol is renewable. Renewable energy is environmentally beneficial because it produces zero or low GHG emissions.

GHG emissions that are created in the WTW cycle are another major factor that should be considered when analyzing the benefits of alternative fuels. GHG emissions are the fundamental cause of the global warming phenomenon. The GHGs from the WTW cycle mainly consist of carbon dioxide, nitrous oxide and methane. A variety of emissions, including GHG emissions, are produced by burning fuels for transportation. In the past few decades, vehicle emissions have been reduced by reformulating fuels to eliminate sulfur and metals by improving combustion and by using post-combustion scrubbing to eliminate unburned hydrocarbons. Unfortunately, emissions (such as CO2) cannot be eliminated because of the existence of carbon in the fuels. In addition, other GHGs are still released throughout the energy life cycle. Fig. 6 shows the overall GHG emissions (g/km) from various fuels during each fuel stage.

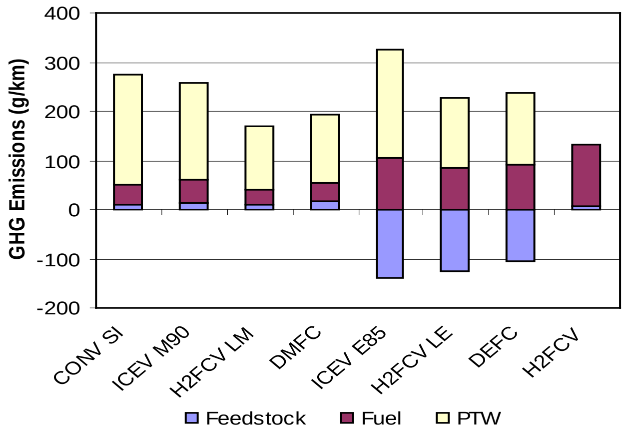

Fig. 6 Various vehicle GHG emissions in each fuel stage

Ethanol fuel produces negative GHGs in the feedstock stage (Fig. 6). Corn production results in a CO_2 sink and releases oxygen as a result of photosynthesis during corn growth. These processes result in negative GHG emission values in the fuel cycle. Although a large amount of GHG emissions are produced during the process, transportation, and distribution of ethanol fuel, the net GHG emissions from corn-based ethanol fuels in the WTP stage are negative. The total GHG emissions produced in each stage for each fuel are presented in Table II. Clearly, the use of ethanol as a fuel appreciably reduced the GHG emissions in the complete energy cycle.

TABLE II TOTAL GHG EMISSIONS IN THE ENTIRE FUEL CYCLE

Vehicle types	GHG emissions (g/km)
CONV SI	274
ICEV M90	259
H2FCV LM	170
DMFC	184
ICEV E85	188
H2FCV LE	103
DEFC	108
H2FCV	134

Among the different technologies that are compared in Fig. 6 and in Table II, the conventional gasoline vehicle emits the highest amount of GHGs and the hydrogen FCV emits the least. Although the hydrogen FCV does not release any pollution during the PTW stage, it produces emissions during the production, transportation, storage and distribution of gaseous hydrogen (the WTP stage). It has been claimed that a hydrogen FCV has zero emissions, which is only correct in the vehicle operation stage.

The methanol-based vehicles resulted in a slight reduction in GHG emissions when compared to a conventional vehicle across the entire fuel cycle. The main GHG contribution of methanol-based vehicles results from their higher PTW fuel economy and the lower carbon intensity of methanol relative to gasoline [15]. The DMFC produces slightly higher emissions than the ethanol reformer fuel cell because of its higher energy consumption in the PTW stage.

IV. DIRECT ALCOHOL FUEL CELL EFFICIENCY SENSITIVITY ANALYSIS

Previous analyses assumed that the DMFC and the DEFC have 35% efficiencies. These technologies are relatively new and are still developing. The recently reported efficiencies are not consistent due to the use of different power ratings, electrodes, electrolyte membranes, and peripheral systems [2, 6, 15]. To fairly assess the environmental impacts of the DMFC and the DEFC, the WTW simulation was performed with DMFC and DEFC efficiencies of between 25 and 45%. Fig. 7 shows the energy consumption and GHG emission simulation results with various DMFC and DEFC efficiencies.

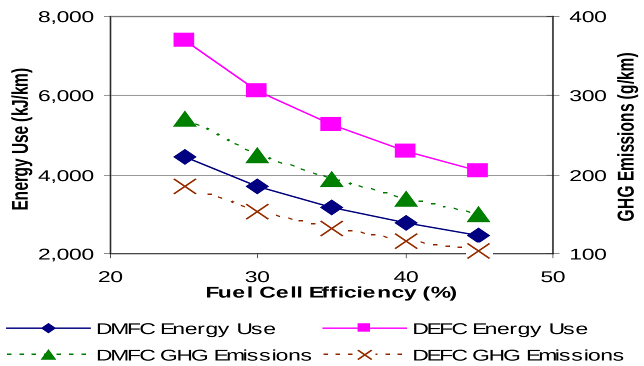

Fig.7 Energy consumption and GHG emissions with different DMFC and DEFC efficiencies

As shown in Fig. 7, when the DMFC and DEFC efficiencies increase, the release of greenhouse gases and the use of energy decrease during the entire fuel cycle. When the DMFC and the DEFC have the same efficiency, a DMFC vehicle utilizes less energy but releases more emissions than a DEFC vehicle. When the DMFC reaches an efficiency of 45%, it can compete with a hydrogen fuel cell with an efficiency of 55%, with respect to energy use and emissions during the WTW cycle. A DEFC vehicle normally generates fewer GHG emissions because of the absorption of CO_2 during corn growth. However, a DEFC vehicle uses much more energy during the entire cycle because of the large amount of energy needed during the WTP stage. Even if a DEFC vehicle has a high (45%) efficiency, the DEFC WTW energy use is approximately equal to that of a DMFC vehicle with an efficiency of 27% and is higher than that of the baseline vehicle. Therefore, switching to a renewable fuel likely achieves the goals of significantly lowering fossil fuel [15] and GHG emissions. However, more energy is used throughout the entire fuel cycle.

V. CONCLUSIONS

The hydrogen fuel cell is considered as an ultimate future fuel for powering vehicles. However, due to safety concerns and the lack of infrastructure, direct alcohols (such as methanol and ethanol) have been studied as an alternative to using hydrogen in fuel cells. Methanol and ethanol overcome the storage and distribution challenges of hydrogen. DMFCs and DEFCs directly convert liquid methanol and ethanol into electric energy without reforming. Thus, their energy efficiency is high. However, the environmental impacts of these alternative fuels should be analyzed for the entire fuel cycle.

A life cycle assessment of alcohol as fuel for medium size passenger cars was conducted using the GREET simulation software. A direct alcohol fuel cell model was developed, and the environmental impacts of the fuels were evaluated. Methanol, synthesized from natural gas, is an alternative fuel for vehicles. The environmental benefits of using DMFCs are distinct when compared to a standard gasoline vehicle. The DMFC significantly reduces both energy consumption and GHG emissions by 30% in the WTW cycle when the DMFC efficiency is 35%. This improvement is attributed to the high PTW efficiency of the DMFC relative to the low efficiency of the combustion engine. If the reaction efficiency of a DMFC is improved, the energy use and emissions will be reduced throughout the entire cycle.

Ethanol is widely recognized as a feasible alternative fuel and is currently being promoted in the transportation sector. As a renewable energy source, the use of ethanol significantly reduces the dependency on fossil fuels for an energy source. This simulation demonstrates that using ethanol reduces fossil fuel usage and increases the total energy consumption when the entire WTW analysis is accounted for. This increased energy consumption is caused by the additional energy used from renewable feedstocks. In contrast, ethanol substantially reduces greenhouse gas emissions by 60% when compared to the baseline (mainly because of the photosynthesis that occurs during corn growth).

The low operating temperature, the high potential efficiencies, the convenience of using liquid fuels, and the absence of a fuel reformer make direct alcohol fuel cells an excellent candidate for transportation applications. In addition, the WTW analysis showed environmental advantages for using methanol and ethanol throughout the entire energy cycle. Direct alcohol fuel cells can compete with the efficiency of fuel cells that have reforming technologies. However, direct alcohol fuel cells avoid the use of a bulky and expensive reformer.

ACKNOWLEDGMENT

The author would like to acknowledge financial support from the University of Mary Hardin-Baylor Summer Research Grant and The Welch Foundation (Grant No. AY-0033).

REFERENCES

[1] C. Lamy, A. Lima, V. LeRhun, F. Delime, C. Coutanceau, and J. M. Leger, “Recent advances in the development of direct alcohol fuel cells (DAFC),” *Journal of Power Sources*, vol. 105, pp. 283-296, 2002.

[2] A. Casalegno, P. Grassini, and R. Marchesi, “Experimental analysis of methanol cross-over in a direct methanol fuel cell,” *Applied Thermal Engineering*, vol. 27, pp. 748-754, 2007.

[3] K. Steckmann, “Extending EV Range with Direct Methanol Fuel Cells,” *EVS24*, Stavanger, Norway, May 13-16, 2009.

[4] J. Wilhelm, H. Janben, J. Mergel, and D. Stolten, “Energy storage characterization for a direct methanol fuel cell hybrid system,” *Journal of Power Sources*, vol. 196, pp. 5299-5308, 2011.

[5] Offenburg students test world’s first direct ethanol fuel cell. [Online]: http://news.mongabay.com/bioenergy/2007/05/worlds-first-ethanol-powered-fuel-cell.html. (Access on February 15, 2012).

[6] D. Chu, and R. Jiang, “Effect of operating conditions on energy efficiency for a small passive direct methanol fuel cell,” *Electrochimica Acta*, vol. 51, pp. 5829-5835, 2006.

[7] T. J. Leo, M. A. Raso, E. Navarro, and E. Sanchez-del-la-Blanca, “Comparative exergy analysis of direct alcohol fuel cells using fuel mixtures,” *Journal of Power Sources*, vol. 196, pp. 1178-1183, 2011.

[8] A. S. Arico, S. Srinivasan, and V. Antonucci, “DMFCs: From fundamental aspects to technology development,” *Fuel Cells*, vol. 2, pp. 133-161, 2001.

[9] H. Dohle, H. Schmitz, T. Bewer, J. Mergel, and D. Stolten, “Development of a compact 500 W class direct methanol fuel cell stack,” *Journal of Power Sources*, vol. 106, pp. 313-322, 2002.

[10] L. H. MacLean, and L. Lave, “Evaluating automobile fuel/propulsion system technologies,” *Progress in Energy and Combustion Science*, vol. 29, pp. 1-69, 2003.

[11] R. Ahluwalia, X. Wang, and A. Rousseau, “Fuel economy of hybrid fuel cell vehicles,” *Journal of Power Sources*, vol. 152, pp. 233-244, 2005.

[12] C. E. Thomas, “Fuel cell and battery electric vehicles compared,” *International Journal of Hydrogen Energy*, vol. 34, pp. 6005-6020, 2009.

[13] U. Bossel, “Efficiency of Hydrogen Fuel Cell, Diesel-SOFC-Hybrid and Battery Electric Vehicles,” *European Fuel Cell Forum*, Morgenacherstrasse 2F, CH-5452 Oberrohrdorf, Switzerland, 2003.

[14] J. M. Ogden, M. M. Steinbugler, and T. G. Kreutz, “A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development,” *Journal of Power Sources*, vol. 79, pp. 143-168, 1999.

[15] L. Gao, “Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions for Alternative Fuels,” *International Journal of Applied Science and Technology*, vol. 1, pp. 1-8, 2011.

[16] X. Ren, P. Zelenay, S. Thomas, J. Davey, and S. Gottesfeld, “Recent advances in direct methanol fuel cells at Los Alamos National Laboratory,” *Journal of Power Sources*, vol. 86, pp. 111-136, 2000.