Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions for Alternative Fuels

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Abstract

Concerns with petroleum oil supplies and greenhouse gas emissions have stimulated research into new alternative fuels, including natural gas, ethanol, methanol, biodiesel, electricity and hydrogen. Instead of only considering petroleum energy consumption and greenhouse gas (GHG) emissions in vehicle operation stages, it is important to analyze the energy use and emissions throughout the whole fuel cycle from well-to-wheels (WTW). In certain cases, energy consumption and/or greenhouse gases can be much larger in the well-to-pump (WTP) stage than in the energy use and emissions produced to propel the vehicle. This paper reviews these fuels, the fuel production pathways and their applications in vehicles. An analysis based on software simulations was performed on each fuel to calculate the total energy use and emissions throughout the entire energy cycle. Results were compared to a conventional gasoline engine vehicle and showed the potential advantages and disadvantages of each alternative fuel.

Keywords: alternative fuel, well-to-wheels, fuel efficiency, greenhouse gas

1. Introduction

The number of vehicles in use has continued to grow worldwide, and the demand for transportation fuels has increased accordingly. Because of the overwhelming use of petroleum as the fuel of choice, these vehicles not only reduce our petroleum resources but also release a large amount of exhaust, largely consisting of carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VO_S), particulate matters (PM) and nitrogen oxides (NO_x), into the atmosphere. These emissions, which can cause global warming, harm the environment, and impact human health, significantly pollute the earth. To address these issues, extensive research and development has been conducted on alternative energy sources for road transportation to supplement oil as the main energy source. Compressed natural gas (CNG), dimethyl ether, methanol, ethanol, biodiesel, electricity and hydrogen, to name a few, have all been considered because of their availability, high energy density, ease of use for vehicles, clean-burning properties and acceptable cost. Although alternative fuels tend to generate lower tailpipe emissions and achieve higher fuel efficiencies than conventional vehicles, it is necessary to analyze the energy use and GHG emissions throughout the whole fuel cycle from well-to-wheels. In some cases, the energy used and GHG emissions produced can be much higher in the well-to-pump stage than the energy used and emissions produced to propel the vehicle in the pump-to-wheels (PTW) stage.

Many studies have been conducted to investigate the WTW energy consumption and GHG emissions of various vehicles and alternative fuels (Demirdoven et al. 2004, Campbell et al. 2009, Williamson et al. 2005, Wang 2002, Brinkman et al. 2005). However, a comprehensive assessment, especially for fuels with commercial availability, has not been fully investigated. In this paper, we present a detailed WTW analysis of the energy efficiencies and emissions of various alternative fuels to understand the environmental advantages, and we propose certain concepts to reduce energy consumption and GHG emissions. This study on the alternative fuels that are available in large volumes should have practical significance with regard to energy application and environmental protection in the near future. Instead of simply listing the comparisons, this paper discusses the reasons that cause the changes in the efficiencies and emissions that are brought about by alternative fuels. The analysis in this paper focuses on alternative fuels rather than on advanced vehicle powertrain (e.g., hybrid vehicles or plug-in hybrids).

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2. Methodology

A well-to-wheels analysis is a systematic approach for assessing the energy consumption and GHG emissions related to different fuels and vehicle propulsion configurations. The whole WTW cycle is comprised of two independent stages, as shown in Figure 1. These include (I) a well-to-pump stage, which includes the recovery or production of the feedstock for the fuel, transportation and storage of the energy source through conversion of the feedstock to the fuel and the subsequent transportation, storage, and distribution of the fuel to the vehicle tank, and (II) a pump-to-wheels stage, which refers to the vehicle operation activities throughout its lifetime (MacLean et al. 2003). Several alternative fuel options, including CNG, methanol, ethanol, biodiesel, electricity and gaseous hydrogen, have been studied as possible replacements for fossil fuels on the basis of WTW analyses. The software Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) was used to model the influences of the alternative fuels on the whole energy cycle.

The current market share for gasoline fuel is approximately half reformulated gasoline (RFG) and half conventional gasoline (CG). RFG possesses the same components as CG, but it is further processed to make it less evaporative, and it contains fewer toxic components and burns easier. Hydrogen can be generated by the steam reforming of natural gas through water electrolysis and from coal gasification. Reforming is the most common process used to satisfy current annual hydrogen consumption. Ethanol is derived primarily from corn, although woody biomass and herbaceous biomass can also produce ethanol. Electricity is generated from multiple sources, including renewable energy (e.g., sun, wind or hydraulic energy), natural gas, oil, coal and nuclear power. Biodiesel, a renewable, clean-burning diesel fuel, is made from an increasingly diverse mix of resources, such as agricultural oils, recycled cooking oil and animal fats. In the United States, biodiesel is mainly produced from soybeans. In addition to natural gas, landfill gas and biomass are also feedstock sources for methanol.

Because passenger vehicles account for over 60% of the total vehicles worldwide (Mierlo et al. 2006), a conventional passenger vehicle using gasoline was selected as the baseline. A fuel cell converts hydrogen and oxygen into water and produces electricity to propel the vehicle using an electric motor. Electricity is used to charge batteries, which are the power source of an electric vehicle. Similar to diesel, biodiesel is burnt in a regular compressed-ignition engine. CNG is used in traditional gasoline engines with modified fuel systems. Ethanol and methanol are normally blended with gasoline for use as motor fuels. Table 1 summarizes the most common fuel pathways of the alternative fuels in 2010 and the vehicle technologies in the models. An important input required for the GREET software is the energy efficiency assumption, e.g., crude oil recovery and refining efficiency or natural gas processing efficiency. Due to the dearth of this type of data in the literature, the fuel production assumptions used in the simulations were the software default values.

3. Results and Discussion

3.1 Pump-to-Wheels Fuel Economy

The PTW efficiency is commonly measured by fuel economy, which refers to the fuel efficiency relationship between distance traveled by a vehicle and the amount of fuel it has consumed. Fuel economy is defined as the distance traveled per unit volume of fuel used, either in kilometers per liter (km/l) or in miles per gallon (mpg). To objectively compare the fuel economies of different fuels, the concept of gasoline-equivalent gallon (GEG) has recently been introduced. A GEG is the amount of an alternative fuel it takes to equal the energy content of one liquid gallon of gasoline (National Institute of Standards and Technology 2007). In this paper, the metric unit of km/l is used, where 1 mpg equals 2.352 km/l. Figure 2 presents a comparison of the average fuel economy in GEGs of passenger vehicles using various alternative fuels.

A battery electric vehicle has the highest fuel efficiency value, although it still experiences some energy losses from battery charge and discharge, storage as well as the motor and power electronics (Eaves et al. 2004). A battery system in an electric vehicle might be as high as 90% efficient in delivering electricity to the motor, which might also have 90% efficiency in converting the electric power to mechanical power. Fuel cell vehicles have complicated drive systems involving compressed hydrogen, the fuel cell and a propulsion system. Fuel cells have high energy conversion efficiencies from hydrogen to electricity of up to 83%. In automotive applications, however, a fuel cell needs a peripheral system, which reduces the net efficiency to approximately 52% (Thomas 2009).

Although fuel cell vehicles are normally much lighter than electric vehicles due to the low energy density of batteries, they also experience energy losses with powertrain components such as the battery, motor and power electronics. (Huang et al. 2011). As a result, the overall PTW efficiency of a fuel cell vehicle is lower than that of an electric vehicle. Other vehicles have much lower efficiencies because they use regular internal combustion engines as their power sources. An engine converts chemical energy to mechanical energy; thus, their maximum efficiencies are relatively low, approximately 32% for gasoline engines and 40% for diesel engines. A fuel cell generates electricity through chemical reactions rather than a thermal reaction; therefore, the efficiency of a fuel cell is not limited by the Carnot principle. Practically, engine efficiencies are much lower than their theoretically maximum values because of energy losses associated with transmission, low power demands and idling operations.

3.2 Well-to-Pump Energy Efficiencies

The simulation results of the well-to-pump efficiencies of alternative fuels are compared in Figure 3. These efficiencies are calculated based on the energy losses that occur along the pathway from the primary energy feedstocks to the fuels that are available from fuel pumps at refueling stations (Wang 2002). The crude-to-gasoline pathway has a high efficiency of 82.6%, which is only lower than the efficiency of CNG production. Natural gas recovery and processing are both 97% efficient (Brinkman et al. 2005). The efficiency of crude oil recovery is approximately 98%, while the refining of CG and RFG is only 89% efficient. The other fuel pathways had lower WTP efficiencies than gasoline. Thus, the vehicles using these fuels must have higher fuel economic values to achieve overall fuel cycle efficiencies.

The least efficient pathway is the WTP cycle of electricity because over 40% of available energy is wasted during electricity generation from natural gas. The use of feedstocks other than natural gas, such as coal, nuclear, or any other feedstock, to create electricity resulted in even higher energy losses during energy conversion. The delivery of electricity to the grid has an average efficiency of 92% (Eberhard et al. 2006). Steam reforming of natural gas is used to produce large quantities of hydrogen and methanol, which is an inefficient method with an energy loss greater than 30%. Hydrogen must be compressed to make it transportable. As a result, additional energy is used during hydrogen compression with a 90% efficiency (Bossel 2003). These factors cause the low WTP efficiency of hydrogen.

Ethanol made from corn and biodiesel from soybeans are classified as renewable energy. Ethanol is produced as a biomass through industrial fermentation, chemical processing and distillation. Biodiesel is typically made by chemically reacting vegetable oil from soybeans with an alcohol. Unlike fossil fuels, which already exist in the earth, biomass fuel production requires extra energy, including nonrenewable energy, to grow corn and soybeans (Shapouri et al. 2002). Thermal and electrical energy are then necessary for the conversion from raw materials to fuels. The production of soybeans that are grown for livestock feed is more energy efficient than corn production because little to no nitrogen fertilizer is needed to produce this legume (Pimentel et al. 2005).

3.3 Well-to-Wheels Energy Analysis

According to the analysis above, some fuels have higher fuel efficiencies in the WTP stage, while others use less energy in the PTW stage. Therefore, the total system energy use for various fuels was calculated in kilojoules per kilometers (kJ/km). Figure 4 shows the simulated energy use for the different fuels throughout the whole WTW cycle. As shown in Figure 4, vehicles using a mixture fuel containing 85% ethanol (E85) consume the most energy, while hydrogen fuel cell vehicles utilize the least energy. E85 uses a considerable amount of energy due to the energy required to grow the corn and then gather, process and transport the corn ethanol. Another reason is that the energy density of ethanol is lower compared to that of conventional gasoline. In this case, the energy used is higher in the WTP stage than the energy used to move the vehicle in the PTW stage.

Natural gas is considered to be the most likely near-term supplement for gasoline and diesel fuels. It has already been used to power internal combustion engines of cars and trucks all over the world. However, from the point of view of energy consumption, a CNG vehicle is not more energy efficient than a gasoline vehicle because it does not decrease the amount of energy used during the whole cycle. Although natural gas uses the least amount of energy during the WTP stage, the low-efficiency engine offsets that advantage in the PTW stage by consuming the most energy.Natural gas can also be used as a feedstock to produce other fuels, such as methanol, which can be used in vehicles at high level blends with gasoline (M90).

Using methanol as a fuel in engines can offer an increased thermal efficiency and increased power output (compared to the base vehicle) due to its high octane rating and high heat of vaporization (Abu-Zaid et al. 2004). Although the use of methanol increases the vehicle operation efficiency, it costs more energy to retrieve methanol from natural gas, with the consumption of 189 kJ/km energy during the feedstock stage and 1446 kJ/km energy in the fuel stage as calculated by the simulation. Blends of biodiesel and conventional diesel are the most commonly distributed products used in the diesel fuel marketplace. Blends of less than 20% biodiesel can be used in diesel equipment with no or only minor modifications required, though biodiesel can also be used in its pure form (National Renewable Energy Laboratory 2009). In this paper, the 20% blend (BD20) was used for this study. One disadvantage of biodiesel is that it tends to reduce engine fuel efficiency, which is caused by the energy content per gallon of biodiesel being lower than that of petroleum diesel (Radich 2004). As a result, biodiesel reduces both WTP and PTW efficiencies when compared to a conventional diesel vehicle, and the total energy use of a BD20 vehicle is higher than that of a gasoline vehicle.

The least fuel consumption is achieved by the fuel cell vehicle on a WTW basis using natural gas as the primary source of hydrogen. The battery electric vehicle consumes slightly more (i.e., 8%) energy than that of the fuel cell vehicle. This was due to the low-efficiency electricity pathway, especially in the fuel stage. Our simulations showed that, during the fuel stage, the energy consumption of electricity is 1495 kJ/km, which is much higher than that of hydrogen (919 kJ/km). It is interesting to note that the energy use of a fuel cell vehicle does not have the best efficiency in either the WTP or the PTW stage, but the sum of the two results in the lowest total system energy use. This high well-to-wheels energy efficiency of the fuel cell vehicle is due to the higher efficiency in converting natural gas to electricity. The most effective approach for improving the electric vehicle WTW efficiency would involve the construction of new, efficient power plants, as some plants that were built in the 1950s only display efficiencies of 25% – 30% during electricity generation (Eberhard et al. 2006).

3.4 Well-to-Wheels Greenhouse Emission Analysis

Besides fuel economy, another major parameter that must be analyzed when considering the benefits of alternative fuels is the overall energy cycle GHG emissions. A GHG is a gas in the atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the phenomenon known as global warming. The main GHGs from the WTW cycle include carbon dioxide, nitrous oxide (N_2O) and methane (CH_4). Other GHG emissions are converted into CO_2-equivalent emissions. Burning fuel for transportation produces a variety of emissions, including GHG emissions. In the past few decades, emissions from vehicles and power plants have been greatly reduced by reformulating the fuels to eliminate sulfur and metals, by improving combustion and through post-combustion scrubbing to eliminate unburned hydrocarbons. However, emissions such as CO_2 cannot be avoided, and other GHGs are still released throughout the energy life cycle. Figure 5 shows the overall GHG emissions (g/km) of various fuels.

Among the simulated alternative fuels, conventional gasoline produces the greatest amount of greenhouse gases per kilometer. CNG reduces the GHG emissions by 15% when compared to gasoline. This reduction comes almost entirely from the PTW stage because of its clean combustion characteristics and high heating value. CNG is essentially methane, i.e., CH_4, with a calorific value of 900 kJ/mol. This burns with oxygen to produce 1 mol of CO_2 and 2 mol of water. By comparison, gasoline can be regarded essentially as benzene, C_6H_6, or a similar compound with a calorific value of 3300 kJ/mol, and it burns to produce 6 mol of CO_2 and 3 mol of water. Therefore, for one mol of CO_2 produced, CNG releases more energy than that released from gasoline and thus reduces GHG emissions (Nitnaware et al. 2011). Methanol produced from natural gas reserves results in a small reduction in GHG emissions throughout the whole cycle. Compared to gasoline, more emissions are released in the WTP stage due to the conversion from natural gas. The benefits are achieved only in the PTW stage, which results from two fundamental characteristics of methanol.

First, as methanol has a lower carbon intensity than gasoline, the GHG emissions are reduced in the vehicle tailpipe. The second one, as discussed before, is from the unique nature of methanol that facilitates higher engine efficiencies. E85 generates much fewer GHG emissions than those of gasoline. It releases a total of only 9 g/km GHG emissions throughout the entire WTP stage, with -73 g/km emissions during the feedstock stage and 82 g/km emissions at the fuel stage. This is the main contribution to its life cycle emission reduction. The corn used to make the ethanol is renewable. It uses CO_2 from the atmosphere while growing. The corn absorbs CO_2 and releases oxygen during photosynthesis, and GHG emissions are therefore reduced. For this reason, the GHG emissions are negative during the feedstock stage.

However, the transportation and processing of corn produces many greenhouse gases. Similar to corn, soybean also produces net negative emissions in the WTP stage in photosynthesis during its growth stage. The combustion engine that emits the second lowest emissions uses BD20 because of the combination of the high efficient diesel engine and the renewable energy contained in the fuel. Electric vehicles are commonly considered zero emission vehicles, as they have no exhaust gases that are emitted directly into the air. However, electric vehicles are not completely zero-emission vehicles because the electricity that charges the battery packs must be generated from other sources. This means that all of the GHG emissions are produced entirely during the WTP stage. For example, burning coal to generate electricity produces tons of carbon dioxide each year that are released into the atmosphere. Figure 5 shows that the total amount of GHG emissions of an electric vehicle is less than the emissions of a vehicle with a conventional combustion engine, but the emissions created during the WTP stage are much more than those by different fuel pathways. A hydrogen fuel cell vehicle does not release exhaust emissions but has greenhouse gas emissions of 157 g/km that are generated during the generation, transportation and storage of hydrogen. From the WTW perspective, it is not a zero emissions vehicle, either. As shown in Figure 5, GHG emissions are reduced by nearly 50% for fuel cell vehicles and approximately 30% for electric vehicles when compared to gasoline vehicles.

4. Conclusion

A life cycle analysis of alternative transportation fuels for passenger cars has been conducted using the GREET simulation software. The analysis was separated into two stages, which consisted of a well-to-pump and a pump-to-wheels stage. A hydrogen-powered fuel cell vehicle consumes the lowest amount of energy and emits the fewest GHGs throughout the WTW cycle. Hydrogen, therefore, is a very promising alternative fuel for transportation. However, the use of hydrogen as a fuel has certain shortcomings and economic problems. One major issue is the cost of developing an infrastructure to support the distribution of hydrogen fuel. In addition, fuel cells are very expensive, and the reliability is low for vehicle applications. Electricity is another encouraging fuel because electric vehicles offer substantial emission and energy benefits. The primary issue with electric vehicles is the distance that they can travel before they need to recharge. Due to the low energy density of batteries, the electric vehicle is an ideal solution for urban mobility and daily commute. The real technical and economic breakthrough in the short or medium term, however, would come from the development of higher energy batteries.

Methanol, a synthesized product from natural gas, is another alternative fuel for engines. The benefits of using M90, however, are almost negligible when compared to the reference case (i.e., a gasoline vehicle). M90 only reduces GHG emissions by less than 2% but considerably increased the energy consumption by 19%. Worst of all, methanol is toxic. If ingested or inhaled, methanol can cause a wide range of harmful effects. According to our simulation results, it is not sensible to use methanol as a fuel at present. When CNG is used directly as a fuel, it reduces emissions by 15% and maintains the same energy use compared to the base vehicle. Accordingly, it is a practical choice as a supplement for gasoline. Ethanol and biodiesel are widely recognized as feasible alternative fuels and are currently being promoted in the transportation sector. As renewable energy, the use of ethanol and biodiesel significantly reduces the dependence on fossil fuels for an energy source. The simulations show that 35% of the total energy used in the life cycle of E85 is from fossil fuels, while BD20 reduces the fossil fuel consumption by 33%. The analysis also demonstrates that while reducing GHG and fossil fuel usage, E85 and BD20 increase the total energy consumption when the entire WTW analysis is accounted for due to the additional energy used form renewable feedstocks.

In addition, the increase in internationally traded food prices in recent years has largely been caused by the increased production of biofuels, especially by ethanol and biodiesel. This reduction in wheat and corn availability, and the resulting price increases, may increase hunger and poverty (Mitchell 2008, Boddiger 2007). As a summary of the results from this study, it is not easy to choose the best alternative fuel among those available in large volumes. On the contrary, it is easier to exclude some of the options that have obvious drawbacks. The availability of natural gas is vast, and it can be used as a fuel or as a feedstock to produce other fuels. Consequently, it could become a substitute for crude oil in the near future. Every other candidate has its own advantages and disadvantages for the transportation sector. An assessment of any energy system is very challenging because of the many factors involved. In general, efficiency and greenhouse emissions are usually the two most important criteria. Cost is another factor that must be carefully considered. Investigations of cost are often associated with other aspects, such as social, economic and environment issues, which are beyond the scope of the technical discussion in this paper.

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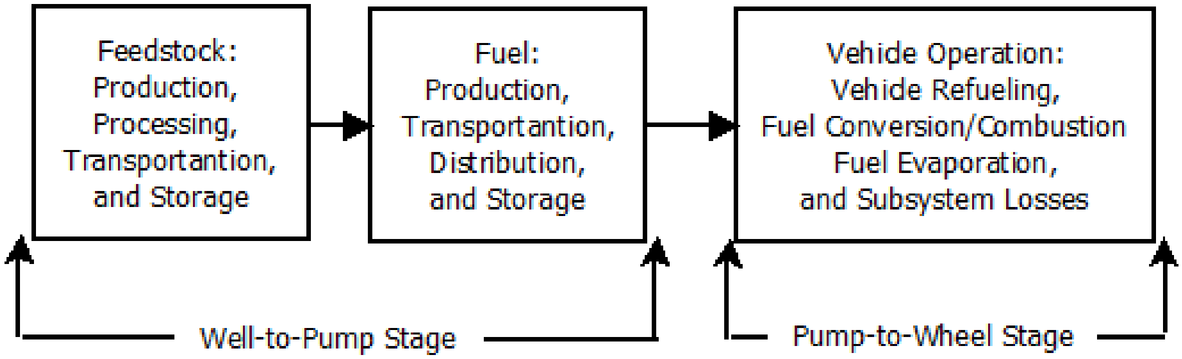

Figure 1. Stages of the energy cycle used in well-to-wheels analysis.

Table 1. Alternative fuel and gasoline pathways and vehicle systems used in GREET simulations.

Fuel	Feedstock	Vehicle Type
Gasoline	Crude oil	Conventional vehicle
Hydrogen	Natural gas	Fuel cell vehicle
Ethanol	Corn	E85 (85% ethanol and 15% gasoline) for conventional vehicle
Electricity	Residual oil, natural gas, coal, nuclear power, and other	Battery electric vehicle
Biodiesel	Soybean	BD20 (20% biodiesel and 80% diesel) for diesel vehicle
Methanol	Natural gas	M90 (90% methanol and 10% gasoline) for conventional vehicle
Natural Gas	Raw natural gas	Conventional vehicle

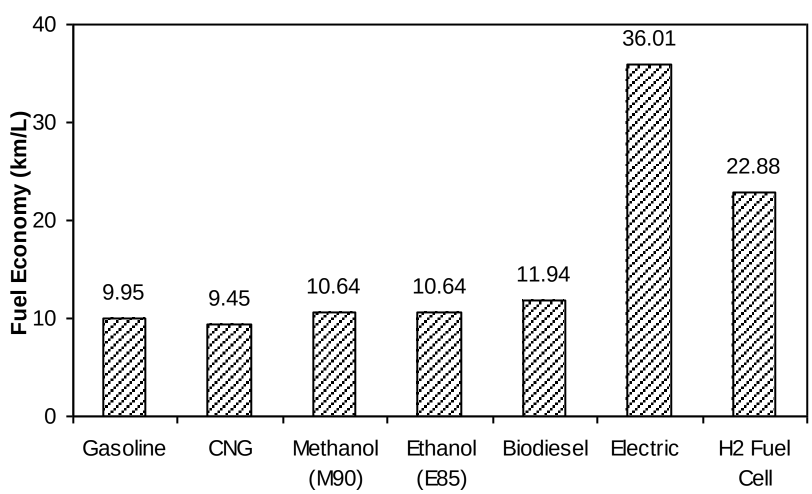

Figure 2. Comparison of the fuel economies for different alternative fuels and gasoline.

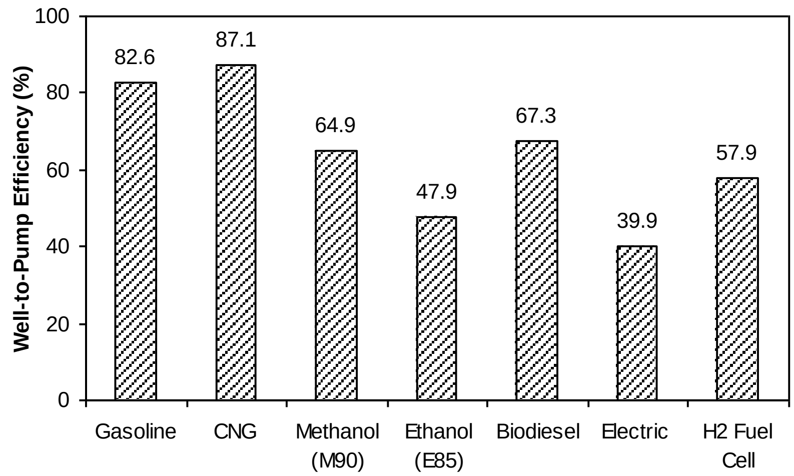

Figure 3. Well-to-pump energy conversion efficiencies for different alternative fuels and gasoline.

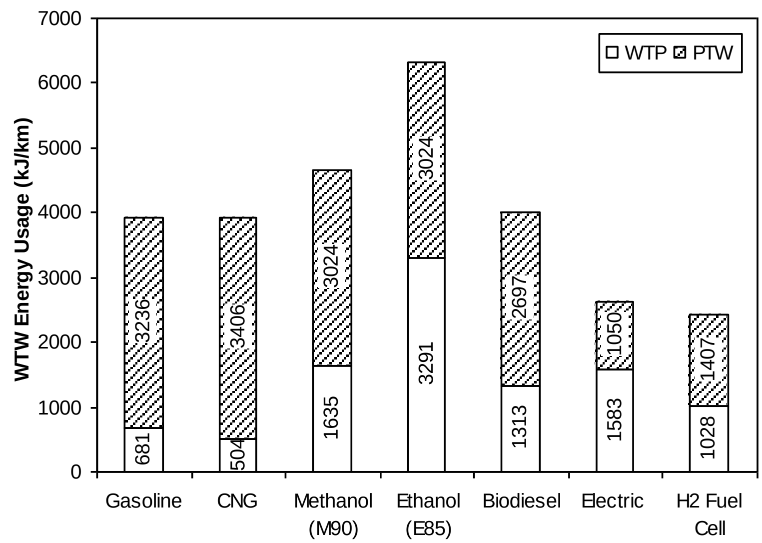

Figure 4. Well-to-wheels total energy consumption for different alternative fuels and gasoline.

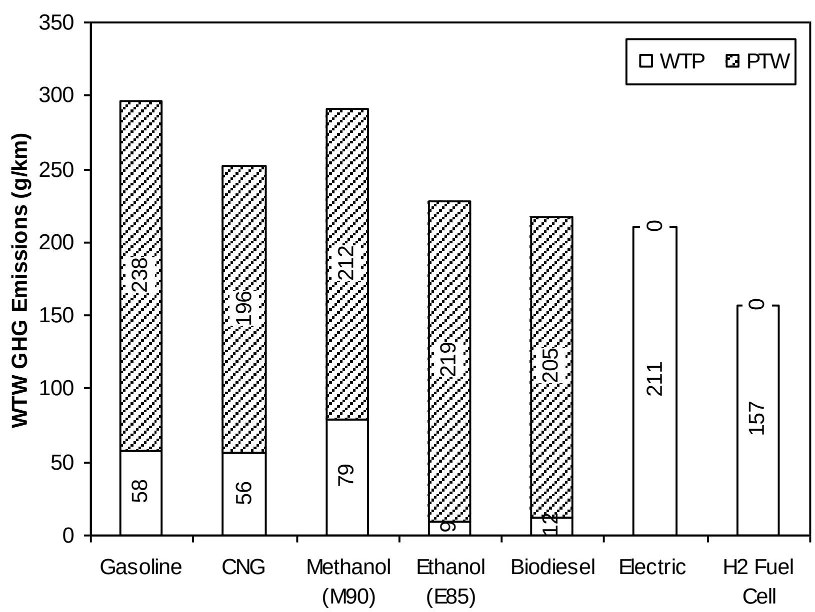

Figure 5. Well-to-wheels greenhouse emissions for different alternative fuels and gasoline.