1-1-2014

A Petroleum Energy, Greenhouse Gas, and Economic Life Cycle Analysis of Several Automotive Fuel Options

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A petroleum energy, greenhouse gas, and economic life cycle analysis of several automotive fuel options

By

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A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Mechanical Engineering
in the Department of Mechanical Engineering

Mississippi State, Mississippi

May 2014

A petroleum energy, greenhouse gas, and economic life cycle analysis of several automotive fuel options

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Title of Study: A petroleum energy, greenhouse gas, and economic life cycle analysis of several automotive fuel options

Pages in Study: 49

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A vehicle fuel's life does not begin when that fuel is pumped into the tank or the battery is charged. Each kilowatt-hour of fuel that is used has a history traceable back to its original feedstock, be it crude oil, corn, solar energy, or others. In this thesis, a life cycle analysis is performed on E10, E85, B20, hydrogen, and electricity, with the well-to-pump fossil fuel energy use and greenhouse gas emissions compared. Results are presented in the form of either energy or mass per kilowatt of fuel at the plug or at the pump. An analysis of the economic viability of each fuel to the consumer is also demonstrated. E85 is found to have the best well-to-pump fossil fuel energy use at 722 Wh/kWh, while hydrogen demonstrates the best well-to-wheel greenhouse gas emissions with 123 g/km (CO_2 equivalent) and electricity produces the lowest vehicle lifetime operating cost of $0.241/mile.

DEDICATION

Whatever is good and perfect comes to us from God above, who created all heaven's lights. Unlike them, he never changes or casts shifting shadows.

James 1:17

While this document is far from perfect, hopefully it is good, and as such it is made possible by our Creator, who is also the original and penultimate engineer. I give glory to God for providing humans with the capability of understanding how a small fraction of His universe works. I feel that he shares the joy of scientific discovery with us.

I have been blessed with a fantastic spouse who supports me and helps me understand the things my feeble mind struggles with. She sets a great example of efficiency and focus. She is the best teammate anyone could ask for.

Sam is the reason I get up every morning (literally) and keeps me going through the day. Just being around him makes everything better.

ACKNOWLEDGEMENTS

I would like to acknowledge my committee, who stuck with me even though this took a while. I would like to thank the Advanced Vehicle Technology Competitions, and especially MSU's team, for providing me the tools to learn about this field. I would like to acknowledge the work of the GREET team at Argonne National Laboratory.

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CHAPTER I

INTRODUCTION

Vehicle fuels are energy carriers; they are a means of storing energy in a transferable and convertible form. Storage can take the form of compounds that release energy through exothermic reactions, such as hydrocarbons used for combustion, or electric energy, stored in a chemical form and converted to kinetic energy through the use of electric motors. Liquid fuels intended for combustion may be refined from fossil fuels or produced from renewable resources such as corn and soybeans.

When examining automotive fuels as possible energy carriers for vehicles, several questions must be asked: which fuels make the best use of natural resources, both domestic and foreign? Which fuels are the most economically viable to the consumer? Which produce the least impact on the environment? Which are the most sustainable for the next ten, fifty, and one hundred years?

The fuel for the previous one hundred years was, without question, petroleum. Almost nothing can rival the energy density of gasoline and diesel. A number of sustainable fuels have made their way into the transportation energy mix, including ethanol and biodiesel. Electricity, the fuel of choice for the very first automobiles, has now come full circle and is a viable transportation fuel again. Gaseous hydrogen used in conjunction with a fuel cell to produce electricity holds tantalizing promise but is still awaiting the technological breakthrough that could make it mainstream.

This thesis will focus on some of the common energy carrier types that are available to consumers in some form today. These include E10, E85, B20, gaseous hydrogen, and grid-generated electricity.

E10 and E85 are blended fuels composed of gasoline and ethanol, containing 10% and 85% ethanol, respectively. Ethanol is an alcohol-based fuel generated from fermentation and distillation of starch crops such as corn, sugar cane, and sweet potatoes. Due to government regulation enacted in 1990, E10 has replaced conventional gasoline at most fueling stations in the US [1-2].

B20 is a blend containing 20% biodiesel and 80% conventional diesel. Biodiesel is an alcohol-based fuel, composed predominantly of methanol and produced from vegetable oils [3].

Gaseous hydrogen may be used either as a direct additive to internal combustion engines or to produce electricity through the use of a fuel cell. This thesis will limit its examination of hydrogen as a fuel to use in a fuel cell.

Electricity is stored in chemical batteries or capacitors and has the unique capability for bidirectional energy conversion. This means that electric energy can either be drawn from an outside source such as the existing electrical grid and stored onboard the vehicle, or converted on-board to and from different energy forms and stored until needed. An example of this bidirectional conversion is transferring power both to and from an electric motor to provide tractive power or recover energy through regenerative braking.

1.1 Method of Comparison

When comparing energy carriers that come in different physical forms it becomes necessary to find a standardized method of comparison. The gallon is a typical unit of measurement for gasoline in the U.S., but there are obvious problems when applying the gallon unit to gaseous hydrogen or electricity. The most straightforward way to compare fuels is to use their specific energies to conduct an energy-based comparison. The energy properties used for the fuels studied in this paper are listed in Table 1.1.

Table 1.1 Table of Fuel Properties

	E10	**E85**	**B20**	**Electricity**	**Hydrogen**
Fuel energy density	11.4 kWh/kg	8.10 kWh/kg	11.5 kWh/kg	N/A	33.3 kWh/kg

1.2 Utility Factor Calculation

Gasoline equivalent units are convenient when comparing individual fuels, but many hybrid electric vehicle (HEV) architectures use multiple fuel sources as energy inputs. One such case is plug-in hybrids (PHEVs), which most commonly use electricity along with a liquid fuel such as E10. This may result in a vehicle with at least two separate modes of operation: charge depleting (CD) and charge sustaining (CS). Charge depleting operation indicates that the vehicle is operating all-electric, using stored electric energy. Charge sustaining operation means that the electric energy storage is neither gaining nor losing a net amount of energy.

A vehicle that uses these two operating modes is known as an extended-range electric vehicle (E-REV). Typically, an E-REV will operate initially in CD mode until its electric energy storage is nearly depleted, then switch to CS mode. Many factors contribute to how much electric energy and how much fuel energy an E-REV consumes, including:

- Daily driving distance
- Energy capacity of its onboard electric energy storage
- How frequently the vehicle is charged
- The vehicle's specific control strategies

Taking into account the national fleet of vehicles, a statistical usage distribution must be considered. The Society of Automotive Engineers (SAE) has defined a procedure for standardizing the fuel usage of electric and liquid fuel vehicle known as utility factor (UF) correction. This calculation uses data taken from over 300,000 vehicles as part of the National Household Travel Survey (NHTS) to estimate the likelihood that a vehicle will be driven a given distance daily [4]. For example, based on data as surveyed during the 2009 NHTS, about 60% of Americans drive 40 or fewer miles each day [5]. This is translated into a PHEV's energy consumption rating by applying the UF, which is 0.6 in our example, as a weighting factor through the following equation [6]:

$$EC = (UF * EC_{cd}) + [(1 - UF) * EC_{CS}] \tag{1.1}$$

Where

EC = Utility factor-corrected energy consumption

EC_{cd} = Energy consumption while charge depleting, and

EC_{cs} = Energy consumption while charge sustaining

Utility factors plotted versus a vehicle's all-electric range are shown in Figure 1.1.

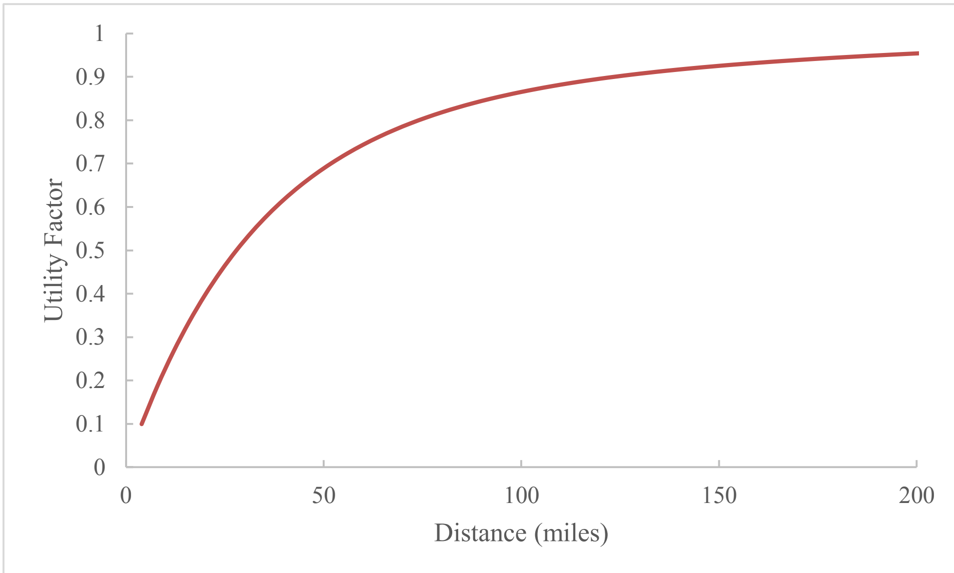

Figure 1.1 Utility Factors versus charge depleting range [6].

The utility factor represents the ratio of miles driven in charge depleting mode vs. the total miles driven and is a characteristic of a vehicle with a given charge depleting range.

1.3 The GREET Model

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, created by Argonne National Laboratory (ANL), is a tool that can analyze vehicle fuel life cycles for present and future fuel sources [7]. This analysis includes the production or collection of the fuel feedstock, the processing of the feedstock into fuel, the transportation of the feedstock and the fuel, and the pump-to-wheels (PTW), or final consumption of the fuel by the vehicle. The model, first developed in 1995, is maintained by a group of researchers at ANL who continually add new fuel pathways such as biofuel from algae and update existing data such as average per-acre yields for feedstock crops such as corn [7]. An example of a fuel pathway included in GREET is ethanol produced from corn, which includes the following steps [7]:

- Fertilizer production
- Fertilizer transportation from plants to farms
- Corn farming
- Corn transportation from farms to ethanol plants
- Ethanol production
- Ethanol transportation from ethanol plants to refueling stations

For each of the steps, the model calculates both energy input and emissions output. Energy input is broken down into specific sources such as natural gas used to run boilers or diesel used for farming tractors. Each process is fully traceable back to its originating energy sources. The GREET model also includes various transportation modes including rail, tanker, barge, truck, pipeline, and others.

Uncertainty analysis was performed on all GREET-modeled energy and emissions numbers. The GREET model includes a stochastic analysis tool which was used for this task. Probability distributions for approximately 800 input variables are defined in the model. Using the Monte Carlo method, the simulation was then run 4000 times. Based on the standard deviation of the results, a 95% confidence interval was determined. These numbers are presented throughout this thesis following a "±" symbol.

CHAPTER II

WELL-TO-PUMP PETROLEUM ENERGY USE

Vehicle fuel life cycle analyses attempt to determine the total fuel usage and emissions generation associated with both the actual on-board usage of the fuel as well as upstream recovery, processing, and transportation. These contributors may be considered independently from both a well-to-pump (WTP) and pump-to-wheels (PTW) standpoint. PTW energy usage is a function of a specific vehicle's powertrain efficiency, while WTP energy usage is a function of a fuel's specific recovery and processing requirements while being transformed into a usable automotive fuel.

Total fossil fuel energy use will be reported in this thesis as well as individual petroleum, natural gas, and coal energy use. Petroleum energy usage is emphasized as a metric due to the reliance of today's most common fuels (E10 and diesel) on petroleum.

2.1 E85

WTP energy usage, which takes into account the energy used producing and transporting fuels, is especially important when examining fuels with high biofuel content. Figure 2.1 illustrates the energy pathways used in E85 production for multiple fossil fuels including petroleum. Coal, natural gas, and petroleum including crude oil and bituminous oil are all used in the production of ethanol. In most cases the primary resource goes through multiple conversions during the WTP process. For example, coal is used to produce electricity, which is used to produce gaseous hydrogen, which contributes to the refining of gasoline, which is used to farm corn. Both conventional and road-certified low-sulfur gasoline are used in the production of E85. Conventional gasoline is used for non-road engines in corn farming and during other energy processing steps, while low-sulfur gasoline is blended directly with ethanol for on-road use. Natural gas is used in every energy conversion process and is the largest WTP fossil fuel contributor for E85. Each line in Figure 2.1 represents a transportation step, which is also included in the WTP petroleum energy usage total. Pathways contributing less than 1% of the total energy contribution for a given process are not included in the diagram but are factored into the final WTP values. This analysis uses projected energy information for the lower forty eight states of the U.S. for the year 2015.

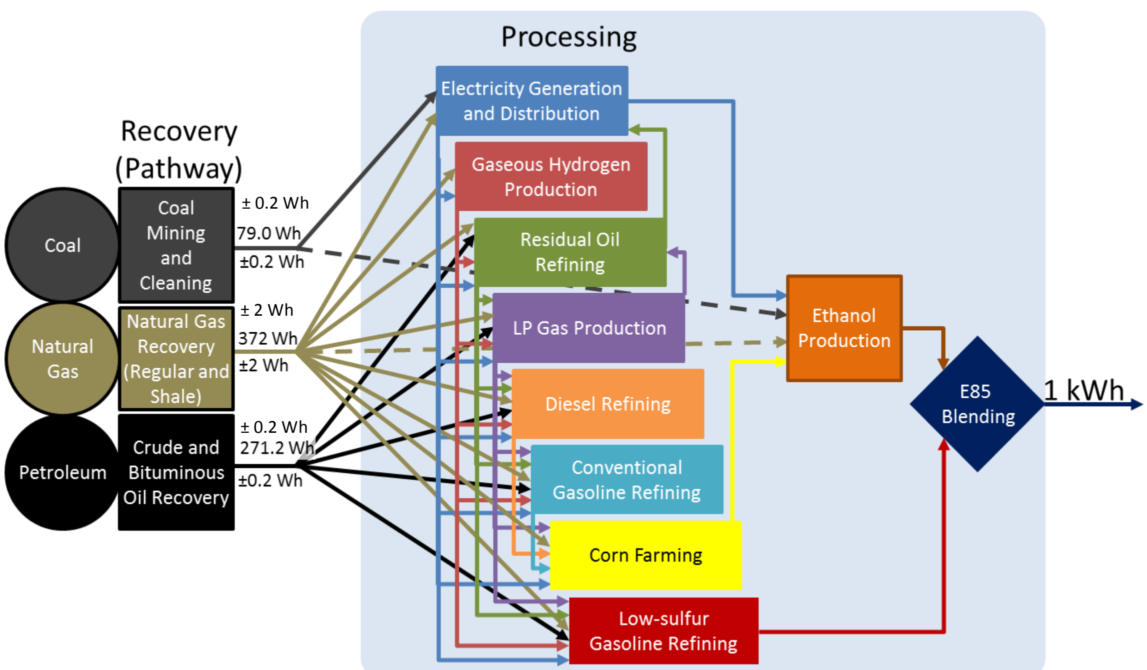

Figure 2.1 Well-to-pump Fossil Fuel Analysis of E85.

Natural gas is the largest contributor of fossil fuel energy used in the production of E85.

For a fuel blend of 85% ethanol and 15% low-sulfur gasoline by volume, 1 kWh of liquid fuel at the pump requires 280 kWh of petroleum. Since Figure 2.1 only shows the fossil fuel energy sources for E85, it is not intended as an energy balance diagram; many renewable energy sources are used as well, including solar energy that through photosynthesis is the primary energy input for the growth of corn [8]. It is an important distinction that E85 designates a blending ratio by volume, not by energy. Since ethanol only has about 67% of the energy density of gasoline, approximately 21% of the energy in E85 comes from its gasoline constituent. For this reason, gasoline WTP factors account for 21%, not 15%, of the final weighted E85 petroleum energy use. A source of debate within the automotive community is whether ethanol has a positive or negative energy balance; that is, does it require greater than 1 kWh of fossil fuel to produce 1 kWh of ethanol? The results of this thesis, in agreement with most recent similar studies, find that ethanol does indeed have a positive energy balance, meaning that the energy contained in the fuel is greater than the fossil fuel inputs required to produce it [9]. Regardless, it is not disputed that gasoline itself has a negative energy balance, requiring over 1.2 kWh of fossil fuel energy to produce 1 kWh of gasoline.

2.2 E10

Figure 2.2 shows the fossil fuel energy flow for E10, which is a blend of 10% ethanol by volume with 90% low-sulfur gasoline. The processing steps for producing E10 are the same as for E85, with a different blend ratio in the final step. The result is that 974 Wh of petroleum energy are used to produce 1 kWh of E10.

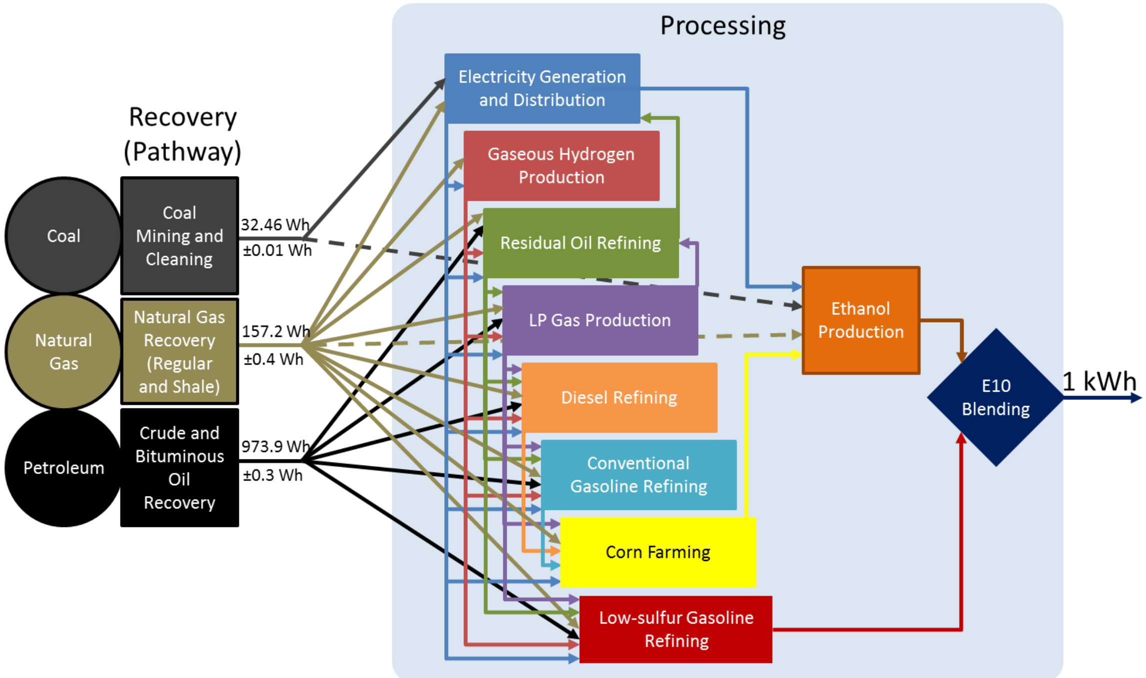

Figure 2.2 Well-to-pump Fossil Fuel Analysis of E10.

Petroleum contributes nearly all of the fossil fuel energy used in the production of E10.

Comparing the WTP factors for E10 and E85 can provide some valuable insight on the use of biofuels in general. While petroleum energy use is reduced by 72% by moving from E10 to E85, natural gas and coal use more than double. According to this study, E85 uses about 38% less total fossil fuels than E10. About 37% of the petroleum used in Figures 2.1 and 2.2 was domestic, while nearly 90% of U.S. natural gas used came from domestic sources [10]. The U.S. is a net exporter of coal [11].

2.3 B20

The production of biodiesel involves more steps than the production of ethanol. While feedstock options are being developed that offer the potential for greater per-acre fuel oil yield, soybeans currently provide the feedstock for nearly all U.S. biodiesel production. Once the soybeans are harvested, their valuable oil must be extracted. Soy oil can then be turned into diesel fuel through transesterification, a process that uses monohydric alcohol in the presence of a catalyst to transform triglycerides, or fats [12]. When that fuel is blended at a 20% by volume level with low-sulfur diesel, the result is that 893 Wh of petroleum energy are used to produce 1 kWh of B20, as illustrated in Figure 2.3. While this may seem an unimpressive reduction in petroleum energy use, it is important to note that the production of 1 kWh low-sulfur diesel actually requires 1,082 Wh of petroleum energy.

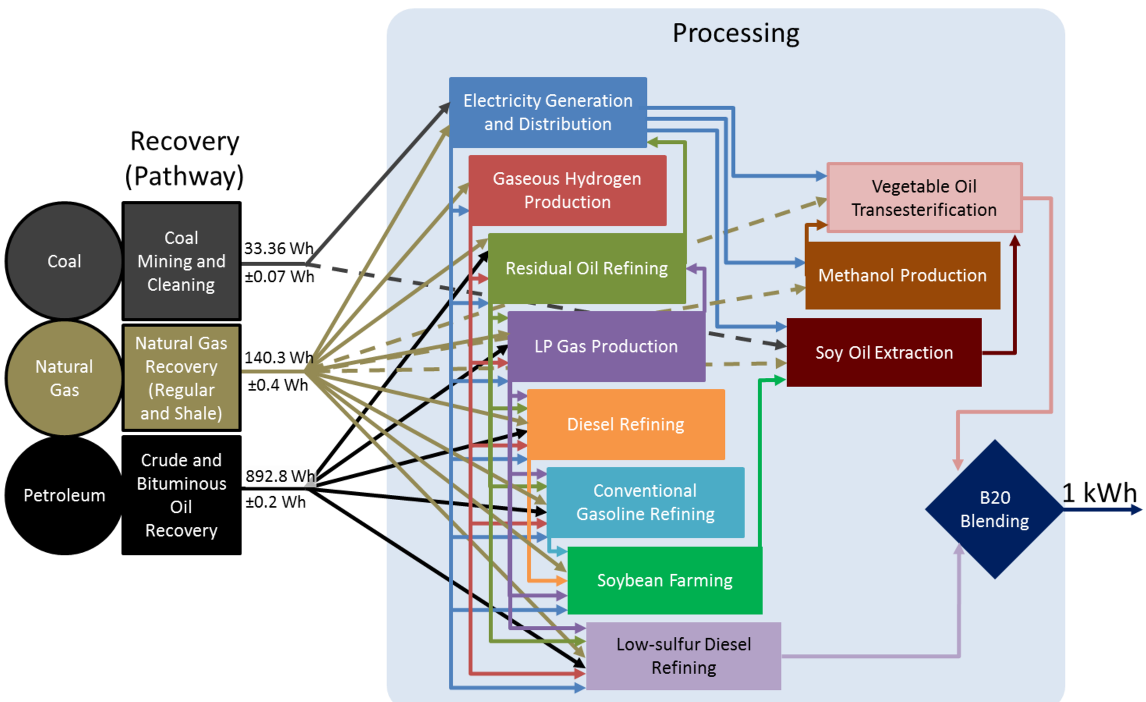

Figure 2.3 Well-to-pump Fossil Fuel Analysis of B20.

Similarly to E10, petroleum accounts for the largest share of the fossil fuel energy used.

2.4 Gaseous Hydrogen

The primary mechanism for gaseous hydrogen production in the U.S. is steam reforming of methane found in natural gas [13]. Compressed gaseous hydrogen produced through this pathway requires very little petroleum: 13.2 Wh per kWh of hydrogen. Production of a single kWh of compressed gaseous hydrogen, however, requires 1,588 Wh of natural gas. For this reason, gaseous hydrogen as a fuel produced through steam methane reformation (SMR) is not currently competitive with biofuels on a cost or environmental basis as an alternative fuel for transportation. Many new hydrogen production techniques being researched have the potential to greatly improve the fossil fuel usage factor [14]. The fossil fuel energy pathways for gaseous hydrogen produced from natural gas through SMR are shown in Figure 2.4.

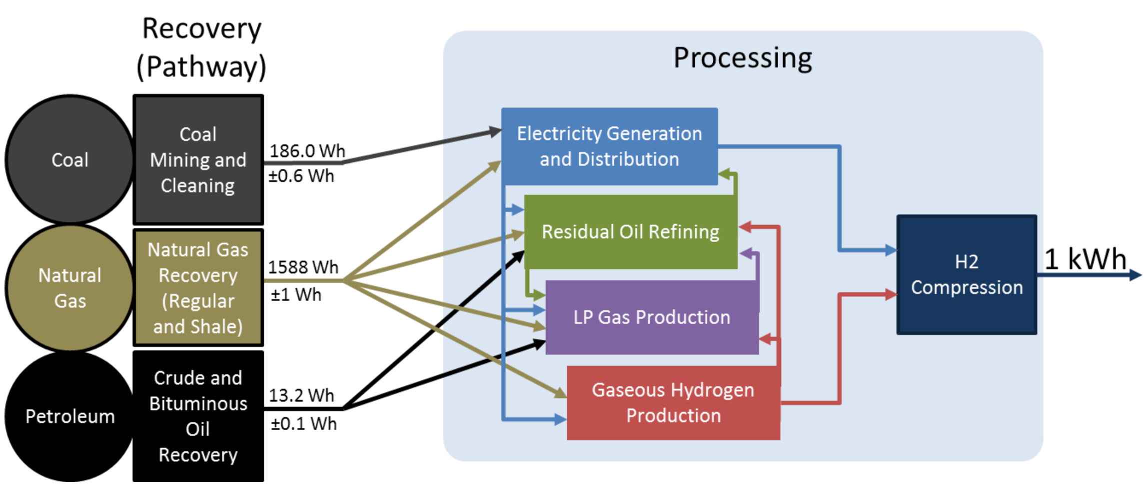

Figure 2.4 Well-to-pump Fossil Fuel Analysis of gaseous hydrogen production from natural gas.

Large amounts of natural gas are required to produce gaseous hydrogen through SMR.

2.5 Electricity

The factors that influence WTP petroleum energy usage for electricity production vary geographically to a greater degree than for other fuels. This is because electricity is more diverse in its available energy inputs and because available resources vary widely by region. Figure 2.5 shows electricity generation energy inputs for the GREET-projected 2015 US average as well as for the Tennessee Valley Authority (TVA), an energy provider servicing part of the Southeast, including Mississippi State, MS. In both cases, coal is the predominant resource used for electricity generation, but the national average relies more heavily on natural gas unlike the TVA mix that uses more nuclear power. This illustrates the importance of specifying region when reporting WTP electricity values.

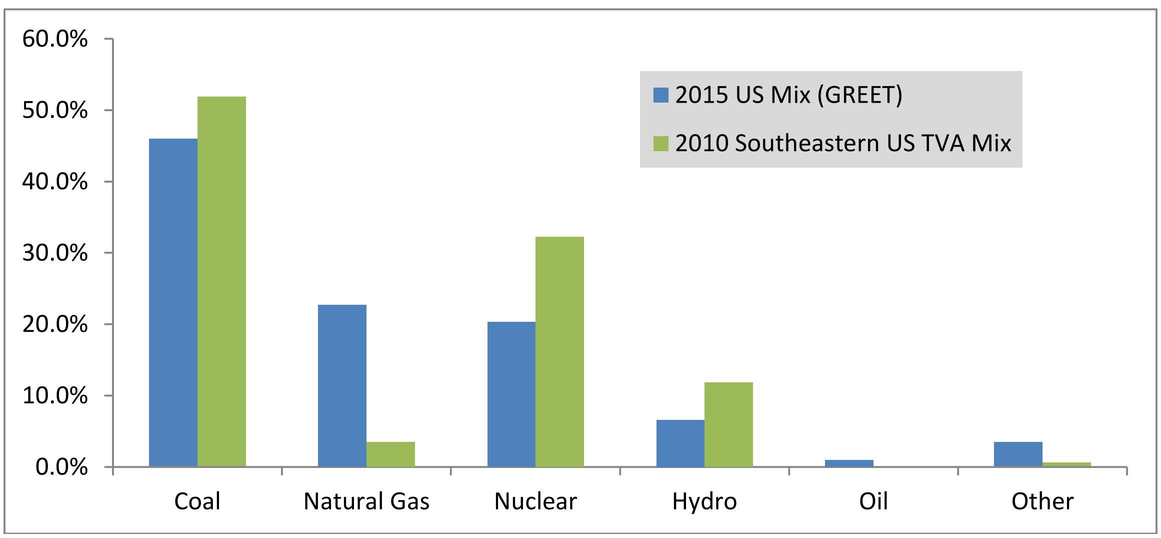

Figure 2.5 Electricity Generation Sources for Southeastern US and national average [15].

The largest share of America's energy come from coal. The TVA mix is slightly "greener," using more nuclear and hydrodynamic power.

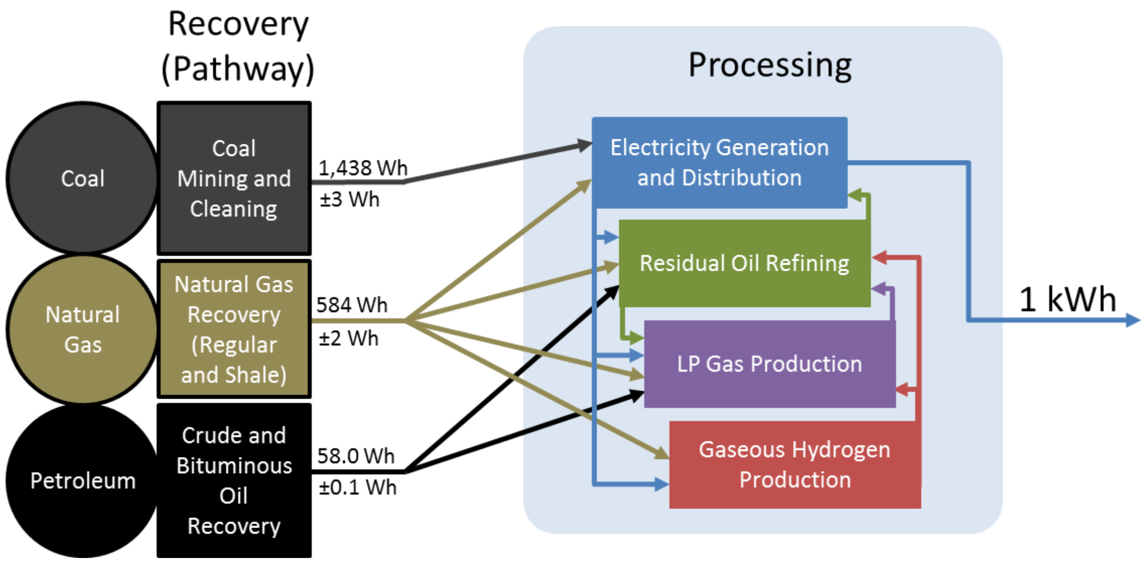

Figure 2.6 Well-to-pump Fossil Fuel Analysis of Electricity Production.

Coal and natural gas are both used extensively in the production of electricity.

As shown in Figure 2.6, for every kWh of generated, transmitted, and distributed electricity, 58 Wh of petroleum are consumed. This petroleum use comes from "peaking generation," which is the short duration use of less efficient but more immediately responsive generation means such as simple cycle oil-fire turbines. Figure 2.7, taken from Shelby and Mui, illustrates a typical daily electric load curve, including the role different energy sources play in meeting demand [16].

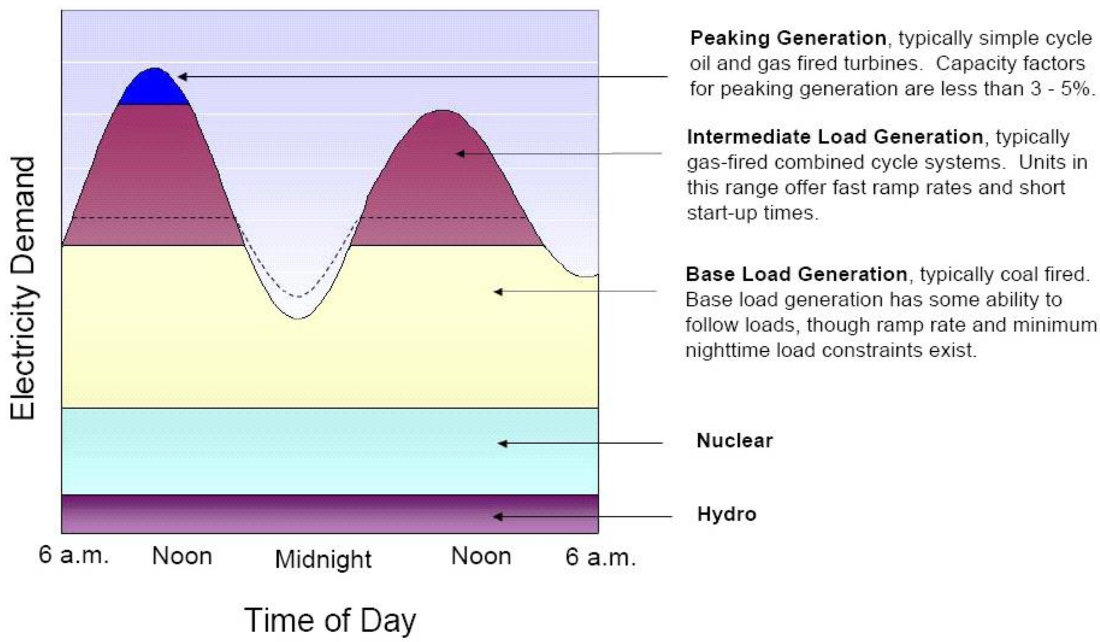

Figure 2.7 Typical Electric Utility Load Curve [16].

The least efficient electricity production methods are also the friendliest for transient operation and are therefore used in high-demand periods.

2.6 Summary

Table 2.1 summarizes the total WTP fossil fuel and petroleum energy usage values for each fuel considered, as well as for several other common fuels as a reference. Uncertainty analysis is not included on the reference fuels.

Table 2.1 Table of Fuel Properties

Fuel	WTP Fossil Fuel Energy Use (Wh/kWh)	WTP Petroleum Energy Use (Wh/kWh)
E10	1,164 ± 0.7	973.9 ± 0.3
E85	722 ± 2	271.2 ± 0.2
B20	1,066 ± 0.6	892.8 ± 0.2
Hydrogen	1,787 ± 1	13.2 ± 0.1
Electricity	2,080 ± 5	58.0 ± 0.1
B100	358	74.4
Low-sulfur Diesel	1,230	1,082
Liquefied Natural Gas	1,237	24.8
Compressed Natural Gas	1,160	5.59
Liquefied Petroleum (LP) Gas	1,168	440

CHAPTER III

WELL-TO-PUMP GREENHOUSE GASES

Greenhouse Gases (GHG) are naturally occurring gases that exist in the atmosphere in order to regulate air temperature by retaining some of the earth's incident solar energy [17]. These gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20), aerosols, chlorofluorocarbons, and water vapor, which is by far the greatest contributor to the greenhouse effect [18]. Some of these gases, specifically CO_2, CH_4 and N_20, are released during the combustion of fossil fuels. In 2011, the U.S. Environmental Protection Agency began regulating the emission of these gases resulting from motor vehicles.

Due to their varying physical properties, the GHG have varying levels of greenhouse effectiveness. The Intergovernmental Panel on Climate Change has quantified global warming potentials relative to CO_2 for each gas [18], which then allows them to be combined into a single GHG value, measured in CO_2 equivalent. This calculation is illustrated below:

$$GHG_{WTP} = (CO_2)_{WTP} + 34 \times (CH_4)_{WTP} + 298 \times (N_2O)_{WTP} \quad (3.1)$$

The GREET model is used to calculate the upstream GHG emissions of each of the five fuels being examined. While GREET does provide results for biogenic CO_2

emissions and removals (sequestration), which consider effects relating to the growth and direct combustion of biomass, those effects are not included here [19].

3.1 E85

Ethanol for E85 blending can be produced using many feedstocks, including corn and switchgrass. Switchgrass is thought to represent a promising future technology, but presently virtually all large-scale ethanol production in the U.S. comes from the dry and wet milling of corn [8]. The GREET model uses a mix of 88.6% dry milling to 11.4% wet milling. Transportation of the final fuel occurs in two stages: transportation to a bulk terminal, which is done primarily by rail according to the GREET model, and transportation from the bulk terminal to refueling stations, which is accomplished entirely by heavy truck.

E85 has the highest WTP GHG emissions of the three liquid fuels that were examined. This is due primarily to two factors: a large amount of nitrogen used in the farming of corn, and a large amount of CO_2 released during dry and wet milling of corn feedstock to produce ethanol. Figure 3.1 shows the individual contributions of the major steps required to produce E85. Ethanol production is the largest single contributor. Since petroleum fuel accounts for only 20.8% of the fuel energy in E85, crude recovery and diesel refining are the smallest contributors.

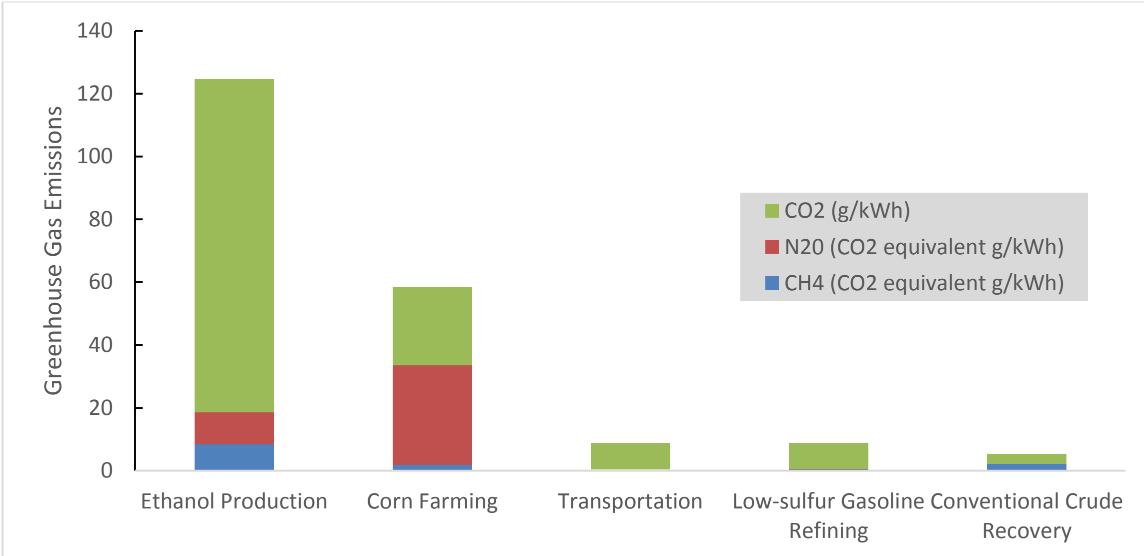

Figure 3.1 Well-to-pump GHG Emissions of E85 Production Steps.

The chemical reactions used to produce ethanol from corn feedstock release large amounts of CO_2.

The total CO_2, CH_4, NO_2 and equivalent GHG emissions values for the production of E85 are shown in Table 3.1.

Table 3.1 WTP GHG Emissions of E85 production

CH_4	N_2O	CO_2	Total GHG (CO_2 equivalent g/kWh)
390 ± 1 mg/kWh	141 ± 3 mg/kWh	150.7 ± 0.4 g/kWh	206.1 ± 0.8 g/kWh

3.2 E10

The biggest contributor to the WTP GHG emissions of E10 is the refining of gasoline, as seen in Figure 3.2. Gasoline refining produces GHG emissions through a number of sources. The most significant of sources are stationary combustion sources such as process heaters, boilers, and combustion turbines. Since petroleum refining typically uses electricity, many refineries produce electricity on-site through co-generation and sell the excess electricity back to the grid. Future work to improve refinery GHG emissions primarily focuses on improving energy efficiency of the refining processes, thereby reducing the GHG emissions [20]. The GREET model uses an average of all U.S. refineries in its calculations.

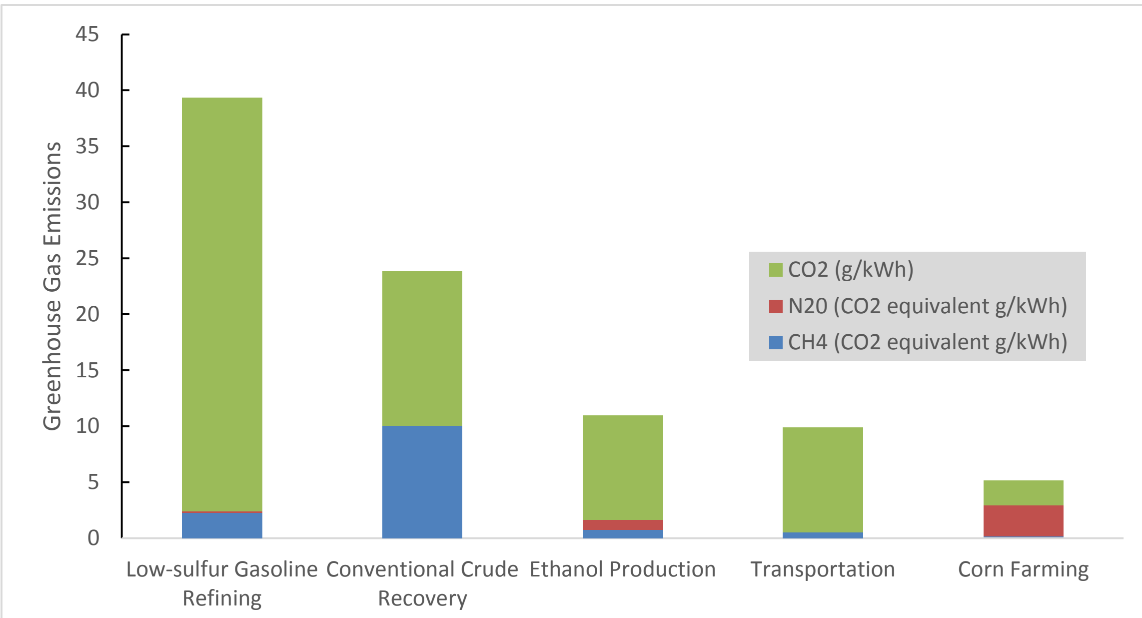

Figure 3.2 Well-to-pump GHG Emissions of E10 Production Steps.

Since gasoline accounts for 90% of E10 by volume, gasoline refining dominates E10 WTP GHG.

The GHG production of gasoline refining is significantly lower than that of ethanol, resulting in much lower WTP GHG emissions for E10 than E85, as seen in Table 3.2.

Table 3.2 WTP GHG Emissions of E10 production

CH_4	N_2O	CO_2	Total GHG (CO_2 equivalent g/kWh)
402.5 ± 0.4 mg/kWh	13.2 ± 0.3 mg/kWh	71.6 ± 0.2 g/kWh	89.2 ± 0.2 g/kWh

3.3 B20

The primary feedstock for biodiesel production in the U.S. is soybeans. In the GREET model simulation, it was assumed that soybeans were the only feedstock for biodiesel production. The production of biodiesel first requires the soy oil to be extracted from the soybeans. Then, soy oil is transformed through transesterification using steam and electricity [21]. These processes also produce useful co-products, such as glycerin. The GREET model takes the co-products into account as either a displacement (GHG saved by not producing the co-products somewhere else) or an allocation (some of the GHG production is assigned to the co-product).

The GREET model indicates that B20 has slightly lower WTP equivalent GHG emissions than E10, as seen by comparing the results for B20 with Table 3.2.

Table 3.3 WTP GHG Emissions of B20 production

CH_4	N_2O	CO_2	Total GHG (CO_2 equivalent g/kWh)
363.8 ± 0.4 mg/kWh	14.96 ± 0.02 mg/kWh	67.5 ± 0.2 g/kWh	84.3 ± 0.2 g/kWh

The most significant contributors to the WTP GHG emissions of B20 are related to petroleum recovery and refining. Soybean farming, similarly to corn farming, produces a larger concentration of N_2O than other processes; this is, again, due to the nitrogen fertilizer used as a farming input. Figure 3.3 shows the contribution of the individual processing steps for producing B20.

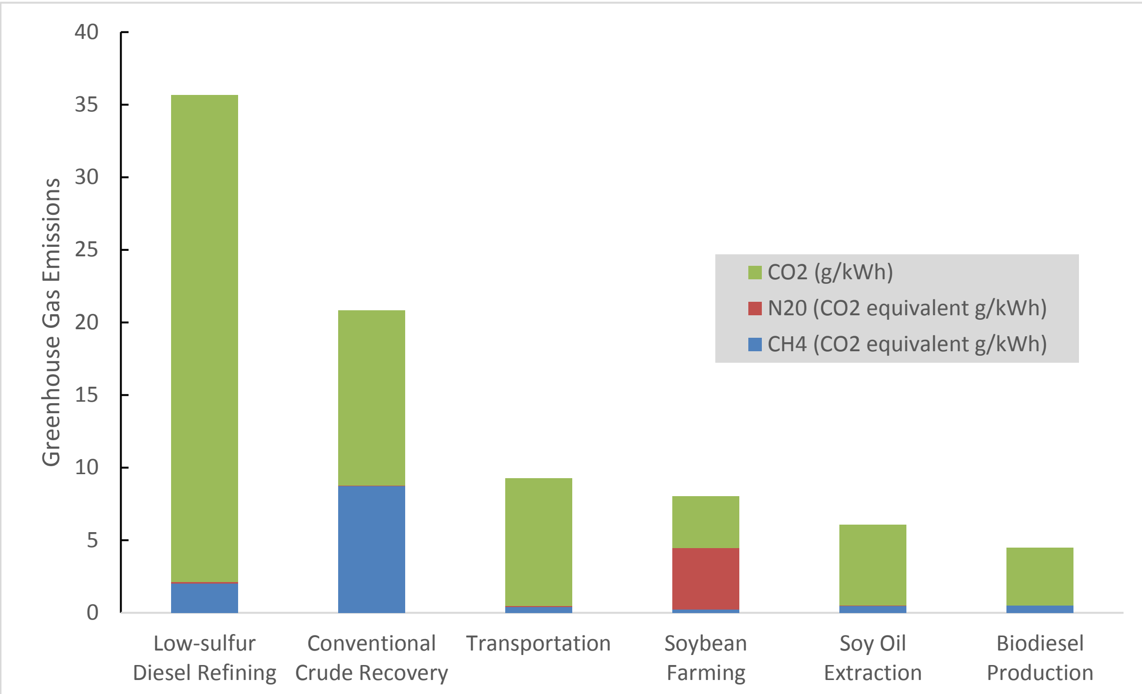

Figure 3.3 Well-to-pump GHG Emissions of B20 Production Steps.

Diesel refining releases the most GHG.

3.4 Gaseous Hydrogen

The primary production of gaseous hydrogen through SMR of natural gas has three primary products: H_2, CO, and CO_2. Hydrogen may also be produced through the electrolysis of water; the large amount of electricity required makes this process unattractive, however, both from an environmental and economic standpoint [22]. For this analysis, SMR is used as the production method for gaseous hydrogen. It is assumed that the hydrogen is produced in a central plant, compressed, and then distributed via tube trailers. The primary feedstock for this reaction is natural gas, transmitted via pipeline.

Since CO_2 is a direct product of the SMR process, GHG are inherently high for gaseous hydrogen produced using this method. The WTP GHG values for gaseous hydrogen are shown in Table 3.4.

Table 3.4 WTP GHG Emissions of gaseous hydrogen production

CH_4	**N_2O**	**CO_2**	**Total GHG (CO_2 equivalent g/kWh)**
840.2 ± 0.5 mg/kWh	2.07 ± 0.01 mg/kWh	370.7 ± 0.4 g/kWh	399.9 ± 0.4 g/kWh

The production of hydrogen alone through SMR produces GHG more than three times that of B20 or E10, not including compression, transportation, or the recovery and processing of natural gas. Electricity used to compress the gas accounts for approximately 10% of the total value. The individual production stages of gaseous hydrogen are shown in Figure 3.4.

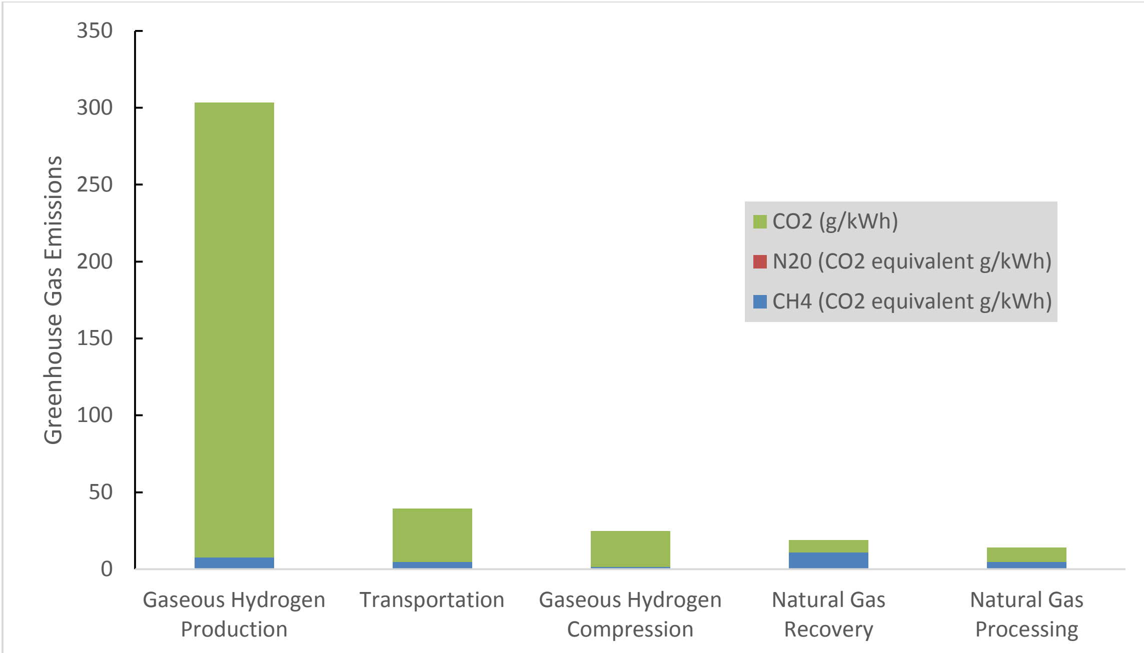

Figure 3.4 Well-to-pump GHG Emissions of Gaseous Hydrogen Production Steps

The chart shows that a large part of hydrogen production GHG emissions come from the production of hydrogen using SMR.

3.5 Electricity

Electricity has by far the highest WTP GHG factor of the examined fuels, at 673.5 g/kWh CO_2 equivalent. This value varies greatly according to what feedstock is used to produce the energy. According to the GREET model, approximately 46% of the electricity used in the U.S. comes from coal-fired power plants, yet these plants account for 73% of the total GHG emissions from electricity production. Another 18% of total GHG emissions comes from natural gas-fired power plants. Approximately 31% of the U.S. electricity generation mix comes from renewable sources such nuclear, hydro, solar, wind, and biomass; these sources, collectively, produce just 2-3% of the total GHG for the electricity generation industry. Losses associated with transmitting and distributing the electricity can be related to 6% of the total GHG emissions. Table 3.5 shows the individual greenhouse gases as well as the overall CO_2 equivalent GHG value. Figure 3.5 shows the contributions from individual generation sources, as well as from transmission and distribution.

Table 3.5 WTP GHG Emissions of electricity production

CH_4	**N_2O**	**CO_2**	**Total GHG (CO_2 equivalent g/kWh)**
1092 ± 2 mg/kWh	8.59 ± 0.02 mg/kWh	634 ± 1 g/kWh	673 ± 1 g/kWh

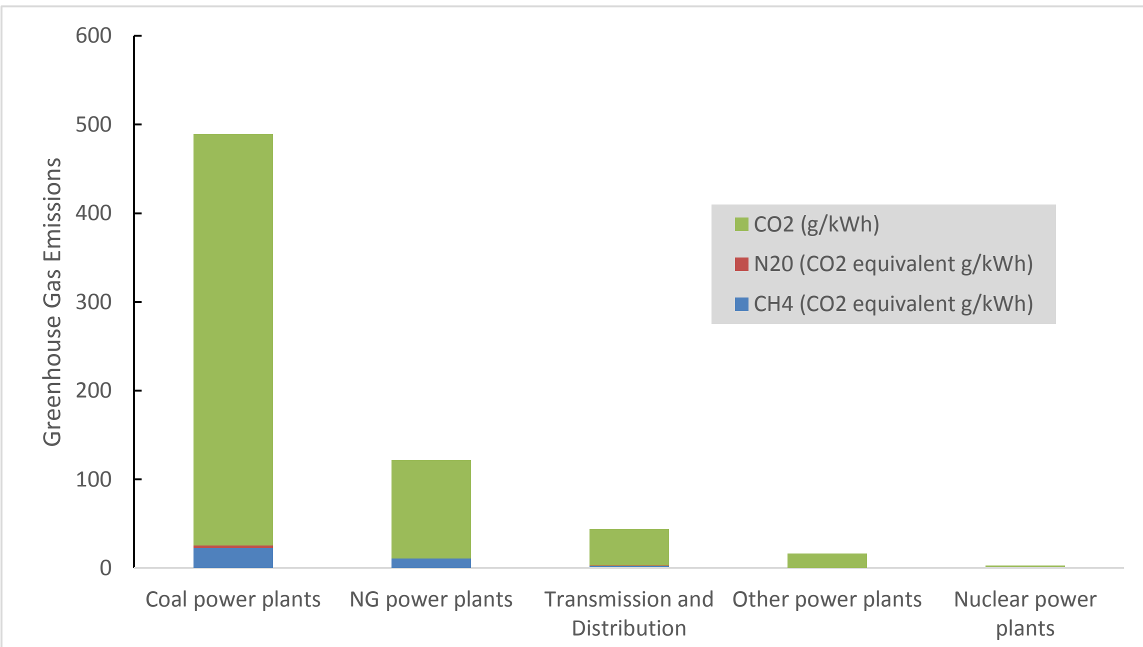

Figure 3.5 Well-to-pump GHG Emissions of Electricity Generation. Coal and natural gas power plants produce the highest GHG emissions.

3.6 Summary

The WTP GHG emissions of the fuels are presented in Table 3.6. The CO_2 equivalent GHG emissions for electricity and gaseous hydrogen are significantly higher than those for the liquid fuels. It is important to note, however, that such great WTP differences do not necessarily hold true when PTW factors are included. Both hydrogen (when used in a fuel cell) and electricity produce zero PTW GHG emissions, while the liquid fuels, when combusted in an ICE, produce CO_2 from the tailpipe. It is also significant that electric and fuel cell powertrains typically achieve efficiencies several times those of conventional powertrains.

Table 3.6 WTP GHG Emissions

	CH_4 (mg/kWh)	**N_2O (mg/kWh)**	**CO_2 (g/kWh)**	**Total GHG (CO_2 equivalent g/kWh)**
E85	390 ± 1	141 ± 3	150.7 ± 0.4	206.1 ± 0.8
E10	402.5 ± 0.4	13.2 ± 0.3	71.6 ± 0.2	89.2 ± 0.2
B20	363.8 ± 0.4	14.96 ± 0.02	67.5 ± 0.2	84.3 ± 0.2
Gaseous Hydrogen	840.2 ± 0.5	2.07 ± 0.01	370.7 ± 0.4	399.9 ± 0.4
Electricity	1092 ± 2	8.59 ± 0.02	634 ± 1	673 ± 1

GREET includes the functionality to model WTW GHG emissions by estimating average values based on fuel carbon content [23], engine characteristics, and fuel evaporation [24]. WTW GHG values calculated using GREET for 2015-model year vehicles using each fuel are shown in Table 3.7.

Table 3.7 WTW GHG Emissions

	CH_4 (mg/km)	N_2O (mg/km)	CO_2 (g/km)	Total GHG (g/km CO_2 Equivalent)
E85 ICE Vehicle	315 ± 1	109 ± 3	311.0 ± 0.6	354 ± 1
E10 ICE Vehicle	345.0 ± 0.7	18.0 ± 0.3	276.0 ± 0.5	293.1 ± 0.5
B20 ICE Vehicle	257.0 ± 0.5	18.0 ± 0.2	237.0 ± 0.5	251.1 ± 0.5
Hydrogen Fuel Cell Vehicle	269.0 ± 0.5	0.526 ± 0.001	114.0 ± 0.2	123.3 ± 0.3
Electric Vehicle	288.0 ± 0.7	2.190 ± 0.006	168.0 ± 0.5	178.4 ± 0.5

When powertrain efficiencies and tailpipe emissions are considered, hydrogen and electricity actually have the least WTW GHG emissions.

CHAPTER IV

VEHICLE LIFETIME OPERATING COSTS

An analysis of fuel characteristics also warrants a discussion of the relative operating costs for vehicles powered by the various fuels. It is inherently difficult, however, to compare and predict vehicle operating costs, for a number of reasons:

- Difficulty in predicting future pump fuel prices
- Variation in individual driving requirements
- Data suggesting that consumer driving habits change when they purchase an HEV or PHEV [25]

This is especially true for EVs and PHEVs, as illustrated by the fact that two recently published high-profile reports had opposite findings on whether or not electric vehicles were sound economic purchases. A report by the U.S. Congressional Budget Office (CBO) states "At current vehicle and energy prices, the lifetime costs to consumers of an electric vehicle are generally **higher** than those of a conventional vehicle or traditional hybrid vehicle of similar size and performance, even with the tax credits […], [9]" while a report by the Electric Power Research Institute (EPRI) claims that for cash purchases "Current PHEVs with incentives are roughly **comparable** in cost to competitive options over the life of the vehicle" and "When compared to the average conventional vehicle, the average lifetime cost of the [Chevrolet] Volt is about $775

lower […]” [25-26]. The 41-page CBO document, which has been widely referenced, contains the words may, might, could, probably, or about (followed by a number) over two hundred times. The following analysis focuses on things that are known using data collected from the current U.S. vehicle fleet and industry standard sources for energy cost projections. It attempts to estimate lifetime costs of representative vehicles powered by the five fuels being studied by examining up-front purchase costs, lifetime fuel cost, and regular maintenance cost. Since hybrid and plug-in hybrid vehicles have fundamentally different powertrains than conventional vehicles, they are considered separately.

4.1 Up-front costs

4.1.1 Hybrid and plug-in hybrid vehicles

HEVs and PHEVs have higher up-front purchase costs than their conventional vehicle competitors. Data comparing conventional E10-powered vehicles to various hybrids and EVs is shown in Table 4.1.

Table 4.1 Comparison of PHEV/HEV Up-front Purchase Costs [25]

Vehicle	**Average Conventional Vehicle**	**Average HEV**	**Chevrolet Volt (PHEV)**	**Nissan Leaf (EV)**
MSRP	*$25,000*	*$30,658*	*$39,995*	*$31,820*
Purchase Price (including taxes, tax credits, destination charges, and charging equipment)	*$26,800*	*$32,865*	*$35,200*	*$29,022*

In Table 4.1, “Average Conventional Vehicle” refers to an average of prices taken from the Honda Civic EX, Chevrolet Cruze LTZ, Ford Focus Titanium, and Volkswagen Passat [25]. “Average HEV” is an average taken using the Ford Fusion Hybrid, Honda

Civic Hybrid, Toyota Camry Hybrid XLE, and Toyota Prius IV [25]. The Chevrolet Volt and Nissan Leaf were chosen to represent the PHEV and EV categories, respectively, because from December 2010 to June 2013 they accounted for 72% of the 98,153 plug-in vehicles sold in the U.S. (excluding Tesla and Fiskar, which are considered luxury brands) [27].

Current U.S. Federal tax credits narrow the gap between conventional vehicles and their HEV and plug-in counterparts; the Nissan Leaf, for example, is within $2,250 of an equivalent conventional vehicle in up-front purchase price when tax credits are considered. It is noteworthy that the 2014 Volt MSRP has been reduced by $5,000, validating the common assumption that economies of scale will reduce the purchase price of future plug-in vehicles.

4.1.2 E85-powered vehicles

Vehicles designed to run on blends of ethanol up to E85 are called flexible fuel vehicles (FFV) [28]. Since this technology requires few hardware changes, up-front costs of FFV are similar in cost to their non-FFV counterparts. Purchase costs are listed in Table 4.2 below for four sedans sold in the U.S. that offer both FFV and non-FFV options.

Table 4.2 Comparison of FFV Up-front Purchase Costs [29-31]

Vehicle	**Average Non-FFV model**	**Average FFV model**
MSRP	*$24,385*	*$25,161*

Vehicle data for the above table was collected for the Buick Lacrosse, Chrysler 200, Ford Taurus SE, and Dodge Avenger. In some cases, the flex-fuel capable engines offered more power than non-flex-fuel engines. There are relatively few FFV options in the U.S. due to the limited availability of high-ethanol blends such as E85.

4.1.3 B20-powered vehicles

Passenger car diesel engines can run on 20% biodiesel blends (B20) [32]. As of 2013 there are a small but growing number of diesel passenger car offerings in the U.S. A survey was completed of the Chevy Cruze, Volkswagen Jetta, Jeep Grand Cherokee, and Audi A8. The diesel variants of these vehicles cost an average of $3,332 more than each vehicle's equivalent gasoline model, as seen in Table 4.3.

Table 4.3 Comparison of Diesel Up-front Purchase Costs [33-36]

Vehicle	Gasoline model	Diesel Model	Difference
2014 Chevrolet Cruze	*$23,305*	*$25,710*	*$2,405*
2013 VW Jetta	*$20,330*	*$23,055*	*$2,725*
2014 Jeep Grand Cherokee	*$36,790*	*$41,290*	*$4,500*
2014 Audi A8	*$78,800*	*$82,500*	*$3,700*
Average			*$3,332*

4.1.4 Hydrogen fuel cell vehicles

Given the extremely limited number of hydrogen vehicles currently available, it is hard to estimate the purchase price of such vehicles. The Honda FCX Clarity is likely the world's first "production" fuel cell vehicle, although production is currently limited to a few hundred. These vehicles currently lease for $600/month, although the automaker almost certainly takes a loss. The U.S. Energy Information Administration (EIA) projects that in 2018, a hydrogen fuel cell vehicle in the compact class would cost $60,600 [37].

4.2 Lifetime Fuel Costs

The CBO report on plug-in hybrids cited in Section 4.1 estimates that a 16 kWh PHEV would have about $7000 lower lifetime fuel costs than an equivalent conventional vehicle, assuming a 150,000 mile vehicle life. This is based on current fuel costs of $3.60/gallon, rising to $3.90/gallon by 2020. Electricity was taken to cost $0.12/kWh throughout the vehicle lifetime. Future fuel savings were discounted at a rate of 10 percent/year, reflecting the reduced value of uninvested future money. Mileage data was taken from the 2009 NHTS report. The CBO study does not include any factors relating to urban versus highway driving miles [9]. The EPRI report cited in Section 4.1 predicts a 150,000 mile lifetime fuel savings of $11,600 for the Chevrolet Volt over a conventional vehicle and $14,600 for the Nissan Leaf over a conventional vehicle. It uses data taken by the National Renewable Energy Laboratory (NREL) in the Puget Sound area of Washington. Fuel costs for this study were $3.62/gallon for gasoline and $0.12/kWh for electricity, with both assumed to stay constant over the life of the vehicle [25].

Both reports estimate that gasoline will remain under $4.00/gallon through at least 2020, and that electricity will remain about $0.12/kWh. These projections concur with the U.S. Energy Information Administration's 2013 Annual Energy Outlook [38] which has key data listed in Table 4.4 below.

Table 4.4 EIA projected fuel costs

Fuel	Current	2025	2040
Gasoline	$3.59/gal [39]	$3.49/gal [38]	$4.32/gal [38]
Diesel	$3.99/gal [39]	$3.97/gal [38]	$4.94/gal [38]
Electricity	$0.1156/kWh [40]	$0.116/kWh [38]	$0.127/kWh [38]

Data was collected in order to estimate the fuel cost per-mile for each fuel type examined in this thesis, based on current fuel prices and average fuel economies. U.S. fuel prices were averaged for the first three months of 2013. Electricity cost was determined by averaging U.S. residential electrical cost over the same time period. There are currently ten active hydrogen fueling stations in the U.S. (nine in California and one in South Carolina); data was taken from three. Average fuel economies were collected from the U.S. Energy Information Administration for a 2013 model year compact passenger car. The findings are shown in Table 4.5 and Figure 4.1.

Table 4.5 Current vehicle fuel efficiencies and average fuel costs

	Average compact car fuel economy (2013)	**Jan-Mar 2013 U.S. fuel prices**
E10 vehicle	35.81 mpg [37]	$3.59/gal [39]
E85 vehicle	27.46 mpg [37]	$3.30/gal [39]
B20 vehicle	47.26 mpg [37]	$4.11/gal [39]
HEV (Toyota Prius)	50 mpg [41]	$3.59/gal [39]
Electric vehicle (Nissan Leaf)	289 Wh/mile [25]	$0.1156/kWh [40]
PHEV40 (Chevrolet Volt)	360 Wh/mile [25], 37 mpg	$3.59/gal [39], $0.1156/kWh [40]
Hydrogen vehicle	17.16 g/mile [37]	$3.66/kg

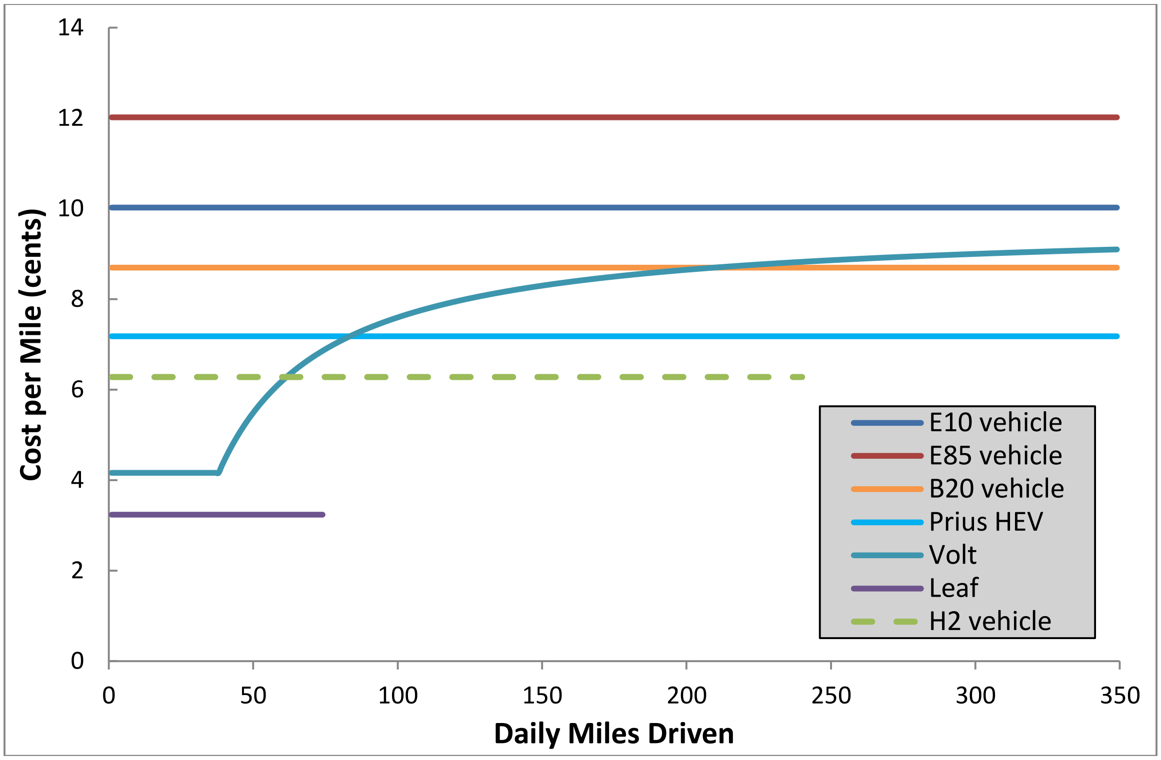

Figure 4.1 Average per-mile fuel costs.

E85 and E10 vehicles have the highest fuel cost, while electric and plug-in vehicles have the lowest.

A conventional vehicle powered by E85 is the most expensive per-mile fuel choice at greater than $0.12/mile. Although diesel costs more at the pump than gasoline, diesel-powered vehicles are more economical on a fuel-cost per-mile basis. The most economical choice is a pure electric vehicle such as the Nissan Leaf that currently costs $0.033/mile or the 2014 Chevrolet Spark at $0.032/mile. The Chevrolet Volt, representing the PHEV category, has efficiency similar to the Leaf while in its initial CD mode but approaches conventional E10 vehicle fuel efficiency over extended distances. The limited range of the EV and the hydrogen vehicle are represented on the figure; given the limited number of data points for hydrogen vehicles, a total range of 240 miles was chosen based on the Honda Clarity FCX.

4.3 Maintenance Costs

To examine vehicle lifetime maintenance costs, regularly scheduled maintenance visits were compared for several vehicles in Table 4.2. The owner's manuals of the specific vehicles were referenced to determine regular service intervals and service items. Some maintenance schedules include different service intervals for "normal" and "severe" operation; in these cases, the "normal" routine was chosen. Service pricing was taken from the website http://www.repairpal.com for the zip code 39762 (Mississippi State, MS). Pricing includes labor and parts, excluding tires. Unscheduled repair visits are not included in this section. Where possible, vehicle models were selected that offered multiple powertrain configurations (such as gas, diesel, or electric). For example, the 2014 Chevrolet Cruze 1.4 L E10-powered vehicle was compared directly to the 2014 Cruze 2.0 L diesel. Vehicle service manuals for flexfuel vehicles do not distinguish between E10 and E85 operation, so scheduled maintenance costs for these two fuels are the same.

The Chevrolet Cruze diesel and Volkswagen Jetta diesel variants have lifetime scheduled maintenance costs that are, respectively, $935 and $1,014 higher than their gasoline equivalents. This corresponds to an average increase of 25.0%. The Toyota Prius scheduled maintenance costs are similar to those of the Cruze; the Volt and Leaf costs, however, are significantly lower. When examining the specific regular service items on a vehicle, it is apparent that a significant portion relate to combustion engine operation. Therefore, it is logical that more electrified vehicles such as the Volt and Leaf would have lower overall maintenance costs.

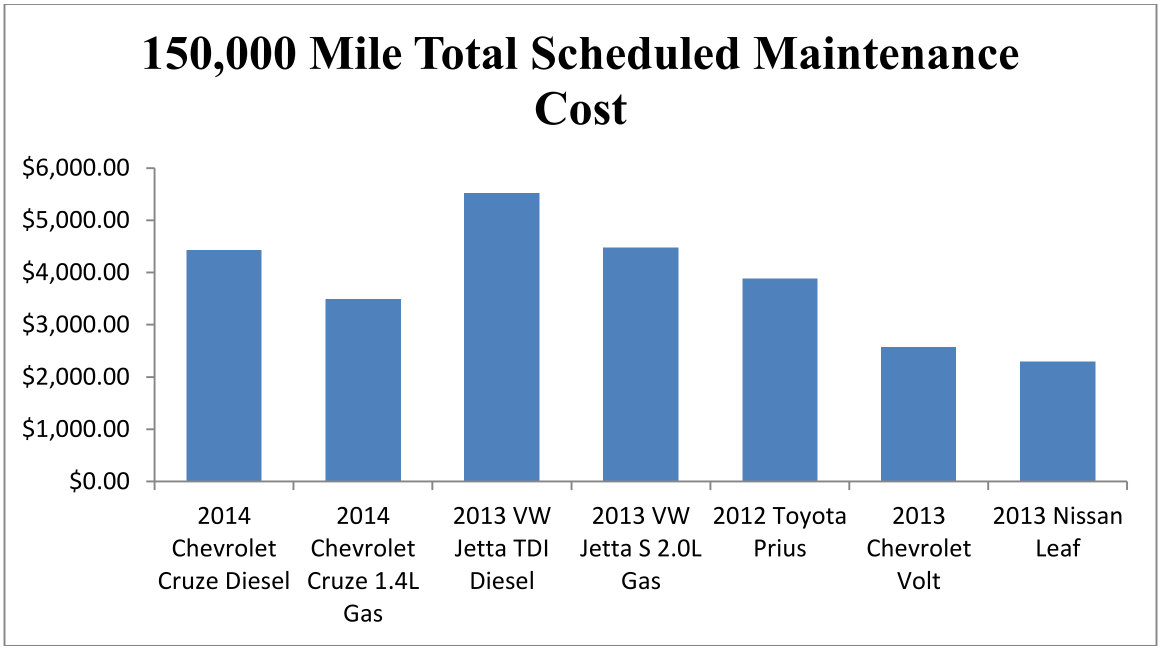

Figure 4.2 Lifetime Scheduled Maintenance Costs.

Diesel vehicles have the highest scheduled maintenance cost, while electric and plug-in vehicles have the lowest.

4.4 Repair Costs

In addition to scheduled maintenance, data was collected to estimate the reliability of different powertrain fuel choices. The website http://TrueDelta.com provides user-based statistics on unscheduled vehicle repair visits. Data was collected for the 2011-2012 Toyota Prius, Nissan Leaf, and Chevrolet Volt. To normalize for different manufacturers quality standards, an average was also taken for four other top-selling models from each manufacturer. Models were chosen that were represented in the survey by at least 30 vehicles and 400,000 total miles. Data specifying gasoline, diesel, or flexfuel were not available, so no comparison was done between E10, E85, or B20. In total, the data examined represents 1,202 cars and over 20 million miles.

Figure 4.3 below shows the number of unscheduled repair visits, per 100 miles, per year for the three hybrid or EV powertrains previously discussed, as well as for the average calculated for each manufacturer. In each case the electrified powertrain had statistically fewer repair visits than the manufacturer's average. This improvement also increases as the extent of electrification increases. The Prius HEV owners reported requiring repairs 48% less frequently than other Toyota owners, while Volt owners required 56% fewer repairs and Leaf owners 76% few repairs than other owners within their brand.

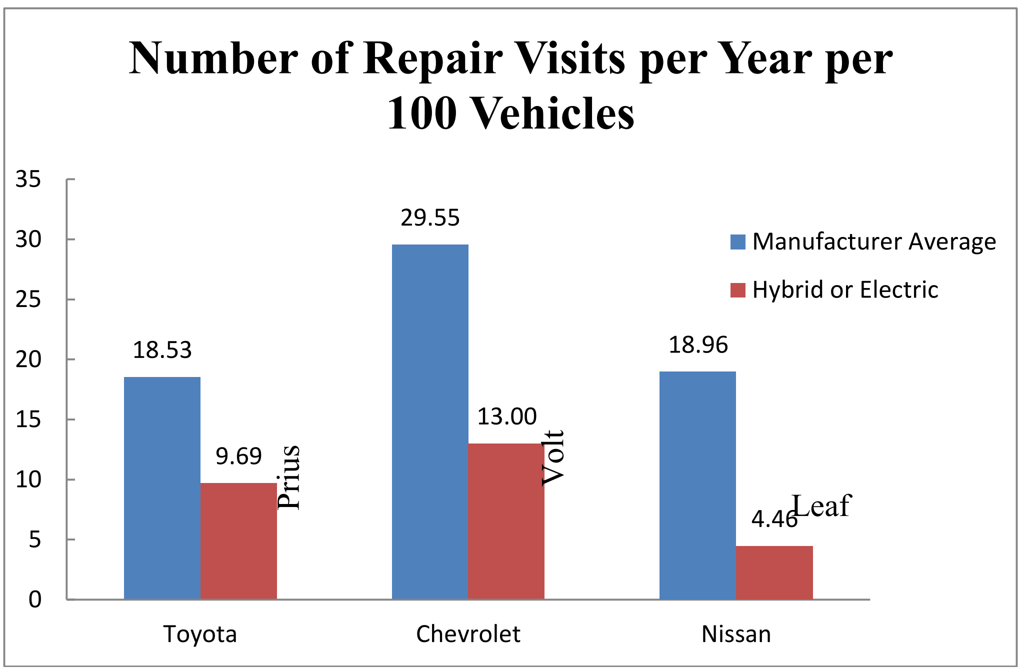

Figure 4.3 Unscheduled Repair Visits.

Hybrid and electric vehicles require less repairs than conventional vehicles.

4.5 Total Lifetime Operating Costs

By using up-front purchase price, lifetime fuel costs, and lifetime scheduled maintenance costs, a total lifetime operating cost model was constructed. Insufficient data was available to attempt to predict lifetime unscheduled repair costs. In an effort to normalize the data for vehicles with similar size and features, the purchase costs for conventional vehicles shown in Table 4.3 was used as a baseline as well as for the purchase cost of E10 vehicles. To determine the average purchase price of E85 vehicles, the average premium paid for FFV was added to this baseline. Similarly, the average premium paid for diesel vehicles was added to the baseline in order to determine B20 vehicle cost. HEV, PHEV, and EV prices are included as listed in Table 4.3.

Lifetime fuel costs were calculated by multiplying the per-mile fuel costs by 150,000 miles, with the exception of the PHEV (as represented by the Chevrolet Volt), which was calculated using a UF of 0.6 [6]. Scheduled maintenance costs for E10, E85 and B20 vehicles were averaged between the models considered in Figure 4.2. The Toyota Prius, Chevrolet Volt, and Nissan Leaf scheduled maintenance costs represent the HEV, PHEV, and EV categories. Total projected lifetime operating costs are shown in Figure 4.4.

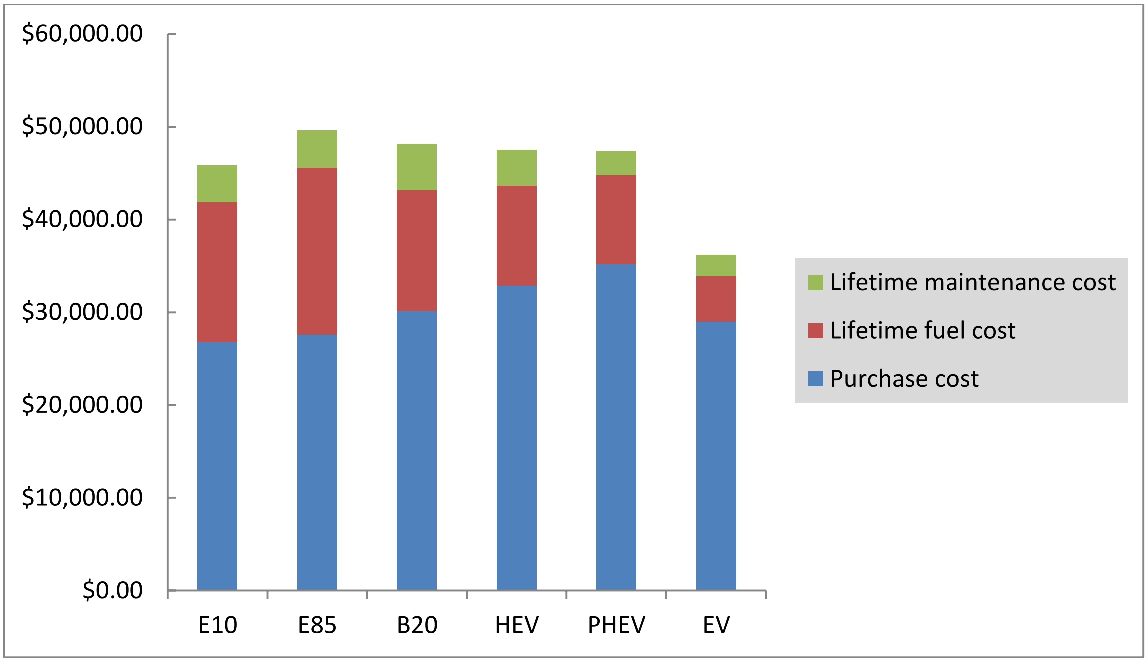

Figure 4.4 Total projected vehicle lifetime operating costs.
Electric vehicles project to have the lowest lifetime ownership and use cost.

The highest projected lifetime operating costs are for the E85-fueled vehicle. This is due primarily to increased fuel cost, which can in turn be attributed to lower energy density of E85 as compared to E10. B20-fueled vehicles have lower lifetime fuel costs, but this is offset by higher purchase and maintenance costs. It is interesting to note that this study projects PHEV and HEV operating costs within $200 of each other over the life of the vehicles. It is also interesting that this study finds that lifetime operating costs of a PHEV are about 3% higher ($1521.91) than those of an E10-fueled vehicle. The lowest lifetime operating costs belong to the pure EV, which comes in 21% or almost $10,000 lower than the E10-fueled vehicle. The 150,000 mile lifetime operating cost for the EV comes in at $0.241/mile.

One additional factor not included in Figure 4.4 is the potential for lower unscheduled repair costs for hybrids and EVs. Figure 4.3 indicates that at least through their first two years of operation, some hybrids and EVs require fewer repairs; sufficient data does not exist, however, to extrapolate this result to the lifetime of the vehicles, especially as the relatively new technology in high-voltage electric energy storage systems ages.

CHAPTER V

CONCLUSIONS

Figure 5.1 illustrates the sharp differences between the fuels in WTP energy usage. While compressed hydrogen and electricity have very low petroleum energy usage as compared to the liquid fuels, this must be weighed against the fact that they also have the greatest total fossil fuel usage. Of the liquid fuels considered, E85 has both the lowest petroleum energy and lowest fossil fuel energy usage.

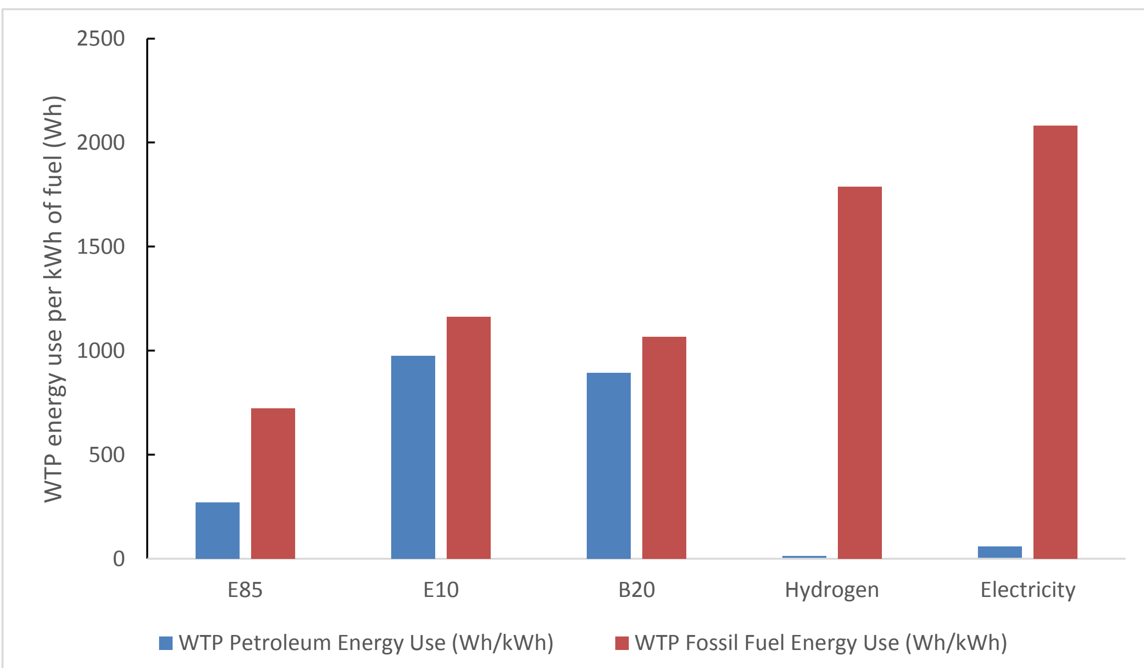

Figure 5.1 WTP Energy Usage Fuel Comparison.

Hydrogen and Electricity use the most fossil fuels in their production, but nearly all of it comes from non-petroleum sources.

Figure 5.2 shows that hydrogen and electricity have the highest WTP GHG emissions; this is overcome, however, by their reduced powertrain emissions relative to conventional powertrains. Hydrogen and electricity also therefore have the best overall WTW GHG emissions. This is a point that is often surprising to the casual observer who surmises that electric vehicles run on electricity generated from coal and, therefore, must produce very high fuel-life GHG emissions.

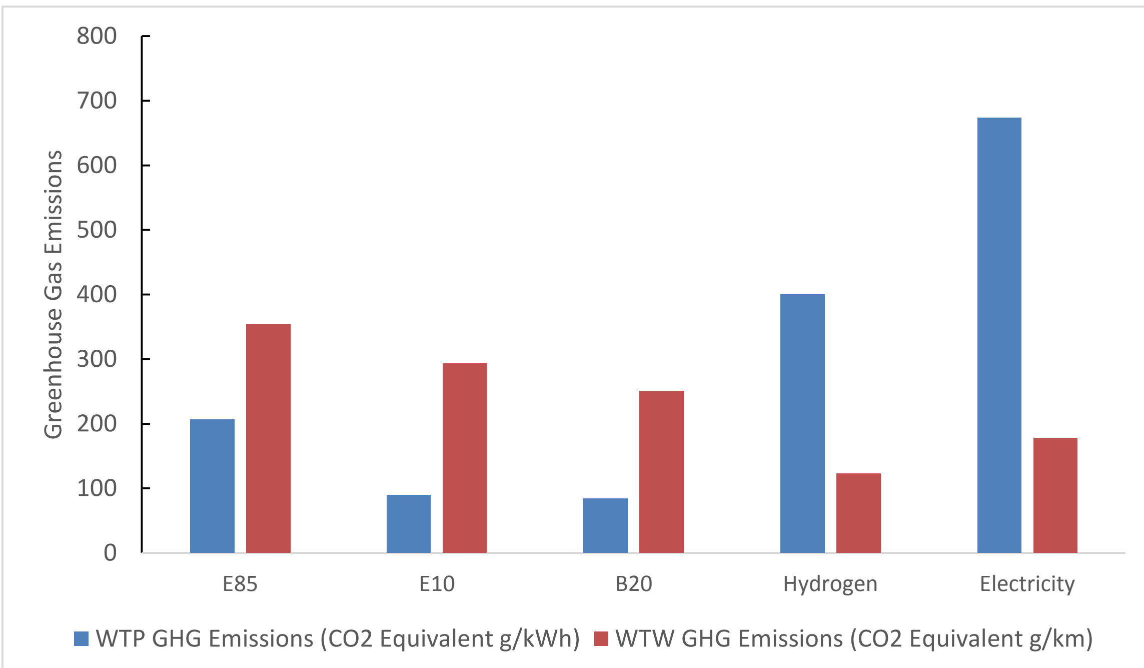

Figure 5.2 WTP and WTW GHG Emissions Fuel Comparison.

B20 produces the least WTP GHG, but hydrogen produces the lowest overall WTW GHG emissions.

Figure 5.3 again presents the summary of lifetime fuel costs for each type of fuel and vehicle. Electric vehicles fare the best, with lifetime operating costs of about $10,000 less than a conventional vehicle powered by E10. This also does not include projected lower repair costs for electric vehicles. Conventional vehicles powered by E85 have the least economical lifetime fuel cost.

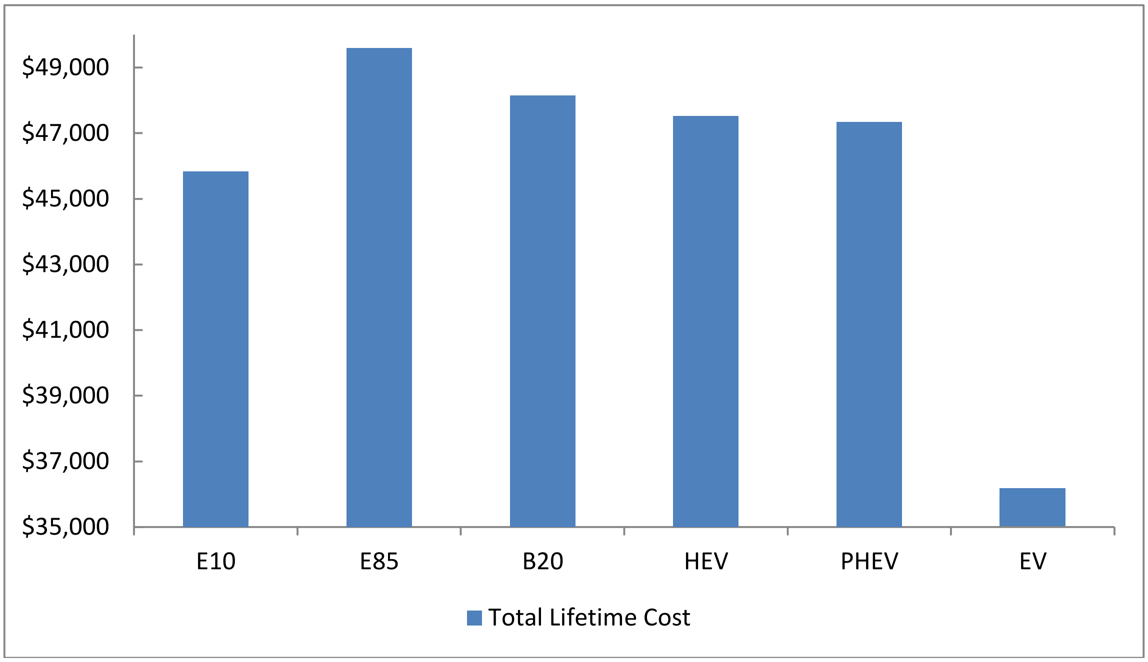

Figure 5.3 Vehicle Lifetime Ownership and Use Cost Comparison.

Electric vehicles provide the lowest lifetime operating cost, due to lower fuel cost and less scheduled maintenance.

The intent of this study is not to determine a winner but to examine the fuel options currently available to automotive engineers and consumers. E85 has the lowest WTP fossil fuel energy use but also has the poorest WTW GHG emissions and fuel cost. Electricity has very good petroleum energy usage, WTW GHG emissions and cost but consumes the most fossil fuels. The "fuel of the future" is likely not a single fuel at all but a conglomeration of the resources available on this planet. For example, General Motors' Advanced Propulsion Technology Strategy (Figure 5.4) proposes a future of hydrogen fuel cell powertrains with hybrids, plug-in hybrids, and electric vehicles serving as intermediary stepping stones [42]. Similarly, Toyota's Strategy for Environmental Technology shows electricity, liquid fuels, and hydrogen each playing a role in their future product lineup (Figure 5.5) [43]. The conclusion of this study matches that of the world's two largest automakers: There is a place for wide variety of fuel sources in the global transportation future.

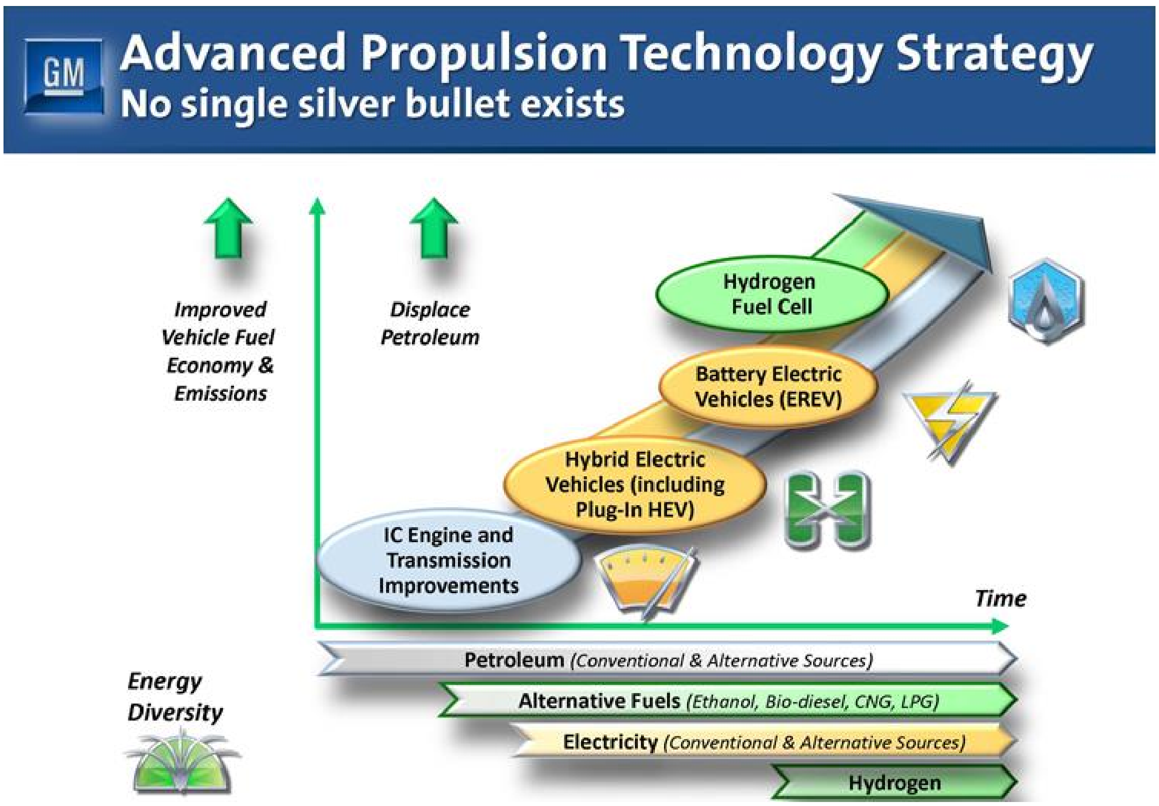

Figure 5.4 General Motors' Future Technology Assessment [42]

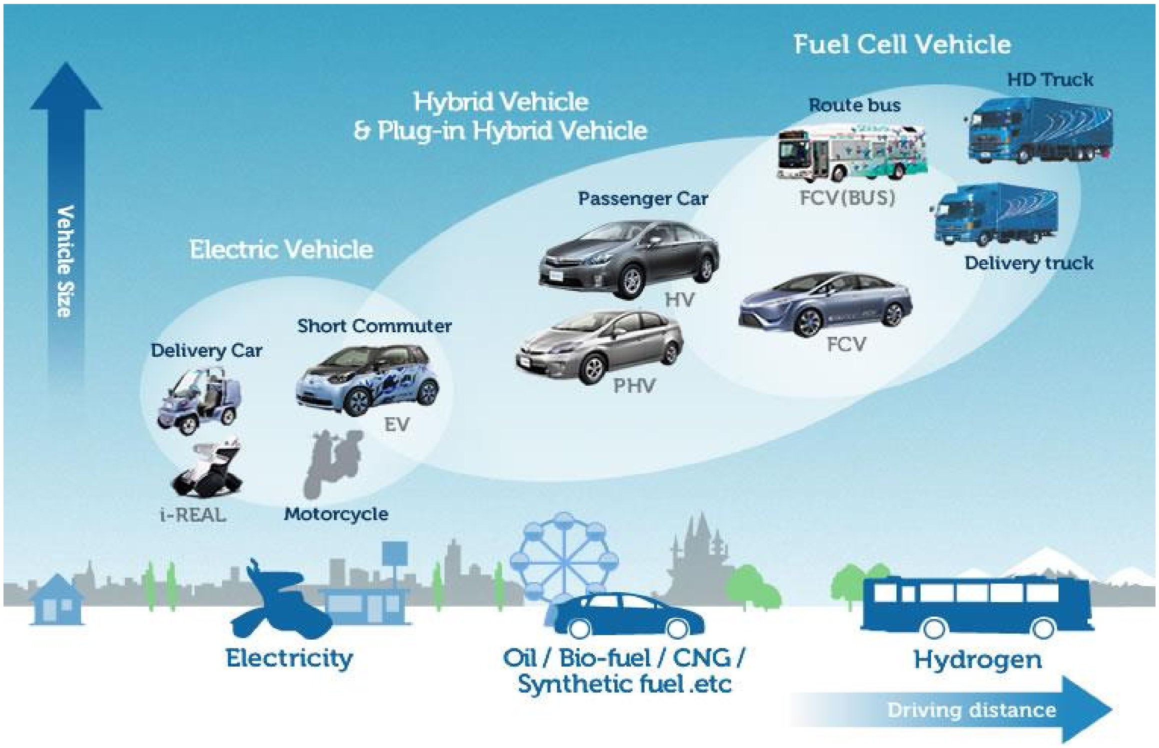

Figure 5.5 Toyota's Strategy for Environmental Technology [43]

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