Greenhouse Gas Emission Impacts of Alternative-Fueled Vehicles: Near-Term vs. Long-Term Technology Options

Michael Q. Wang

Center for Transportation Research
Energy Systems Division
Argonne National Laboratory
Bldg362/B215
Argonne, IL 60439

Phone: (630) 252-2819
Fax: (630) 252-3443
E-mail: mqwang@anl.gov

Drafted on February 12, 1997
Revised on May 20, 1997

Paper to be Presented at the 8th Global Warming International Conference
New York City, May 25-28, 1997

Abstract

Alternative-fueled vehicle technologies have been promoted and used for reducing petroleum use, urban air pollution, and greenhouse gas emissions. In this paper, greenhouse gas emission impacts of near-term and long-term light-duty alternative-fueled vehicle technologies are evaluated. Near-term technologies, available now, include vehicles fueled with M85 (85% methanol and 15% gasoline by volume), E85 (85% ethanol that is produced from corn and 15% gasoline by volume), compressed natural gas, and liquefied petroleum gas. Long-term technologies, assumed to be available around the year 2010, include battery-powered electric vehicles, hybrid electric vehicles, vehicles fueled with E85 (ethanol produced from biomass), and fuel-cell vehicles fueled with hydrogen or methanol. The near-term technologies are found to have small to moderate effects on vehicle greenhouse gas emissions. On the other hand, the long-term technologies, especially those using renewable energy (such as biomass and solar energy), have great potential for reducing vehicle greenhouse gas emissions. In order to realize this greenhouse gas emission reduction potential, R&D efforts must continue on the long-term technology options so that they can compete successfully with conventional vehicle technology.

Introduction

In the world's developed countries, the transportation sector accounts for a large portion of total greenhouse gas (GHG) emissions. For instance, the share of carbon emissions by the transportation sector in the "Group of Seven" countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) is over 30% of total carbon emissions (EIA 1994). On the other hand, although transportation GHG emission share in developing countries is moderately low now, the rapid expansion of the transportation sector in developing countries is expected to increase its share. Reductions of transportation GHG emissions are critical to reductions of overall GHG emissions for alleviating global warming effects.

Three general approaches can be taken to reduce transportation GHG emissions. The first approach is to reduce motor vehicle usage. In particular, vehicle miles traveled (VMT), which are far greater in industrialized countries than in developing countries, may be reduced through such transportation control measures use of public transit systems and carpooling. However, it is very unlikely that VMT in developing countries can be reduced, since the value of VMT per capita there is still very low. In contrast, VMT in developing countries is expected to increase significantly. The second approach is to increase transportation energy efficiencies. Improvements in vehicle fuel economy directly result in reduced fuel consumption per VMT. In general, motor vehicles in developing countries are still very inefficient and have large potential for fuel economy improvements. The third approach to reducing transportation GHG emissions is to switch transportation fuels from carbon-rich petroleum-based fuels, such as gasoline and diesel, to low- or non-carbon fuels. This paper analyzes GHG emission impacts of fuel switches for motor vehicles. It is demonstrated that the use of alternative-fueled vehicles (AFVs) results in changes in vehicle fuel economy, as well as changes in fuels. Both fuel switches and fuel economy changes by use of AFVs are considered.

One may draw conclusions about CO_2 emission impacts of different fuels solely from carbon contained in each fuel. For example, on the basis of carbon content ratios for different fuels as presented in Table 1, one may conclude that relative to use of gasoline, use of H_2 can eliminate CO_2 emissions, while use of ethanol may have little effect on GHG emissions. However, the primary resource used to produce a fuel and the upstream fuel production activities for the fuel differ among fuels. To fully and correctly estimate GHG emissions, one should consider the full fuel cycle from primary energy recovery to on-vehicle fuel combustion. In this paper, fuel-cycle GHG emissions are estimated for various AFV types.

Table 1. Carbon Ratio of Different Transportation Fuels Relative to Gasoline (based on same energy content for each fuel)

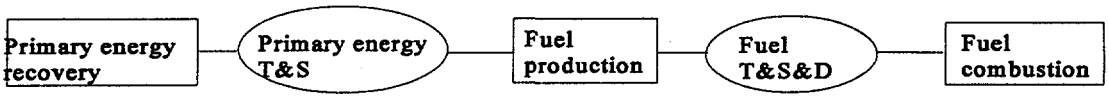
Fuel	Carbon ratio (based on same energy content)
Gasoline	1
Diesel	1.062
Methanol	0.954
Ethanol	0.996
Liquefied petroleum gas	0.945
Dimethyl ether	0.939
Natural gas	0.789
Hydrogen	0

GHG emission impacts of AFVs depend on type of fuels used, type of primary energy sources used to produce the fuels, and energy efficiencies of vehicles, as well as upstream energy production activities. A fuel-cycle model has been developed at Argonne National Laboratory (ANL) to estimate fuel-cycle emissions and energy consumption of various AFV types. The model, called Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET), calculates fuel-cycle energy use and emissions. GREET is used here to analyze fuel-cycle GHG emission impacts of near-term and long-term AFV technology options.

The GREET Model

For a given transportation fuel, a fuel cycle includes the following chain of processes: primary energy recovery; primary energy transportation and storage; fuel production; fuel transportation, storage, and distribution; and vehicular fuel combustion (Figure 1). Usually, fuel-cycle activities before vehicular fuel combustion are referred to as upstream activities. In this paper, primary energy resources are referred to as energy feedstocks such as crude oil, natural gas, and coal; fuels are

referred to as gasoline, diesel, electricity, etc.



Note: T&S — transportation and storage T&S&D — transportation, storage, and distribution

Figure 1. Flow Chart of a Fuel Cycle

Energy is consumed and emissions are generated during upstream fuel-cycle activities, as well as during vehicular activities. In each upstream activity, fossil energy is burned and emissions are generated. Also, fuel leakage and evaporation that ultimately generate emissions are associated with upstream activities. The GREET model calculates fuel-cycle energy use and emissions for various fuel-cycle paths (Wang 1996).

The GREET model calculates fuel-cycle grams-per-mile (g/mi) emissions and Btu-per-mile (Btu/mi) energy use for various fuel cycles. GREET includes emissions of volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxide (NO_X), particulate matter with size smaller than 10 microns (PM_{10}), sulfur oxides (SO_X), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The three GHG gases (CH_4, N_2O, and CO_2) are further combined together with their global warming potentials as CO_2-equivalent GHG emissions. GREET calculates energy consumption for three types of energy: total energy (all energy sources), fossil energy (petroleum, natural gas [NG], and coal), and petroleum only. For a given fuel-cycle stage, energy use (in Btu per million Btu of energy throughput) is calculated. The calculated total energy use for the particular stage is allocated into different process fuels (e.g., NG, residual oil, diesel, coal, and electricity). Fuel-specific energy use, together with emission factors of the combustion technology for a specific fuel, is then used to calculate combustion emissions for the stage. GREET has an archive of combustion emission factors for various combustion technologies fueled with different fuels and equipped with different emission control technologies. Combustion emission factors for VOC, CO, NO_X, PM_{10}, CH_4, and N_2O for combustion technologies are derived primarily from U.S. Environmental Protection Agency's (EPA's) AP-42 document. SO_X emission factors for most fuels are calculated on the assumption that all sulfur contained in process fuels is converted into sulfur dioxide (SO_2). CO_2 emissions are calculated with a carbon balance approach; that is, the carbon contained in the fuel burned, minus the carbon contained in combustion emissions of VOC, CO, and CH_4, is converted to CO_2.

Emissions of VOC, CO, and NO_X from vehicle operations for gasoline vehicles (GVs) and diesel vehicles (DVs) are calculated with EPA's Mobile5a model, which calculates on-road per-mile emissions from motor vehicles for the three pollutants. Emissions of PM_{10} for GVs and DVs are calculated with EPA's Part5 model, EPA's Mobile5a-equivalent model for calculating PM and SO_X

emissions. GVs are treated as benchmark vehicles. Vehicular emissions from AFVs are calculated within GREET by using benchmark GV emissions and emission reduction rates by AFVs relative to benchmark GVs. SO_X emissions from each vehicle type are calculated within GREET on the assumption that all sulfur contained in fuels is converted into SO_2; emissions of CH_4 and N_2O are estimated from some existing data sources; and CO_2 emissions are calculated by means of a carbon balance approach.

The previous version of GREET — GREET1.0 — was documented by Wang (1996). Revisions have been made regarding some key emissions and energy use assumptions. The current version — GREET1.3 — is used to calculate emissions of the three GHGs for this paper. Emissions of the five criteria pollutants are not addressed in this paper.

Near-Term and Long-Term AFV Technology Options

In this paper, near-term technology options are those technologies that are already available, while long-term technology options are those expected to be available in 2010 and beyond. Near-term technology options include internal combustion engine vehicles fueled with M85 (85% methanol and 15% gasoline by volume), E85 (85% ethanol and 15% gasoline by volume), liquefied petroleum gas (LPG), and compressed natural gas (CNG). Furthermore, it is assumed that methanol is produced from natural gas; ethanol, from corn; LPG, from petroleum and NG; and CNG, from NG. These vehicle types and fuel production technologies are already in the marketplace. As of 1995, in the United States, there were nearly 300,000 LPG vehicles, 93,000 CNG vehicles, 20,500 methanol vehicles, and 850 ethanol vehicles (EIA 1995). These vehicles consumed 294 million gasoline-equivalent gallons of LPG, 67 million gallons of CNG, 6.5 million gallons of methanol, and 189,000 gallons of ethanol (additional 871 million gallons of ethanol were consumed in the form of gasohol — a blend of 90% gasoline and 10% ethanol by volume) (EIA 1995). Over time, it is expected that these vehicle technologies will continue to be improved and their market barriers will become less severe.

The long-term AFV technology options considered in this paper include battery-powered electric vehicles (EVs), hybrid electric vehicles (HEVs), fuel-cell vehicles (FCVs) fueled with hydrogen or methanol, and ICEVs fueled with E85. Furthermore, it is assumed that methanol will be produced from natural gas, hydrogen from natural gas and solar energy via electrolysis of water, and ethanol from biomass. While these long-term technology options are not yet commercially ready, they offer great GHG emission reduction potential.

Use of EVs in the United States has been pushed by regulations in California, Massachusetts, and New York that require a certain given percentage of future new vehicle sales to be EVs. Consequently, General Motors has already begun to sell its two-seat EV1 in California and Arizona. Other auto manufacturers will have EV models for sale soon. HEVs and FCVs offer a large potential for improving fuel economy and reducing emissions. The Partnership for a New Generation of Vehicles (PNGV) program in the United States is investigating HEV and FCV technologies for achieving the program's goal of tripling vehicle fuel economy (National Research Council 1996).

Currently, hydrogen is produced primarily from natural gas. Production of hydrogen from solar energy via water electrolysis is now prohibitively expensive. But the technology offers great energy and environmental benefits. It is hoped that research and development (R&D) efforts in this area will bring the technology's cost down so that widespread use of the technology will be possible. Ethanol from both woody and herbaceous biomass enables the transportation sector to use renewable energy sources. The technology offers great energy and GHG benefits. R&D efforts are being made in the U.S. to reduce the cost of the technology.

Key Assumptions Regarding Vehicle Technologies

This paper considers alternative-fuel applications for passenger cars only. For the near-term technology options, it is assumed that spark-ignition engines will be powered by M85, E85, LPG, and CNG. A model-year 2000 gasoline car is selected as the benchmark vehicle for near-term technology comparisons. The gasoline car is assumed to have a fuel economy of 28 miles per gallon (mpg) (EIA 1997). Vehicles fueled with pure methanol and ethanol experience cold-start difficulties. Thus, it is assumed here that M85 and E85 will be used. The high octane value of M85 and E85 can help increase engine compression ratio, thus improving fuel economy. It is assumed M85- and E85-powered passenger cars will achieve a fuel economy improvement of 5% over the fuel economy of gasoline cars. LPG and CNG can improve engine efficiency as well. However, the extra weight of CNG cylinders can have a large fuel economy penalty. It is assumed that CNG-powered cars have a 10% fuel economy penalty. On the other hand, the weight penalty of LPG tanks is small. It is assumed that LPG-powered cars have the same fuel economy as gasoline cars do.

A model-year 2010 benchmark gasoline car is selected for long-term technology comparisons. The gasoline car is assumed to have a fuel economy of 30.5 mpg (EIA 1997). It is assumed that E85 is used for spark-ignition engines, with a 5% improvement in fuel economy over the benchmark gasoline car.

FCVs, which convert the energy of chemical reactions into electricity, can be clean and highly efficient. This paper considers the proton exchange membrane (PEM) fuel cell, which offers high power density and fast startup time and is appropriate for vehicle applications. It is assumed that H_2-powered FCVs will achieve fuel economy twice as high as that of the benchmark gasoline car and will have zero vehicular GHG emissions. Furthermore, it is assumed that gaseous hydrogen is compressed at service stations at 5,000-6,000 psi and stored on FCVs.

Various hydrogen-containing fuels, such as methanol, ethanol, and other hydrocarbon fuels, can be used in FCVs. These fuels are either converted into hydrogen by on-board reformers or used directly in fuel cells designed to do so. Development of commercially ready direct carbon-based fuel cells still faces many technical challenges. This paper considers PEM fuel cells equipped with reformers. Only methanol-powered FCVs equipped with methanol reformers are considered here, because methanol reformers are more mature than other reformers. The fuel economy of methanol-powered FCVs is calculated on the basis of the fuel economy of hydrogen-powered FCVs and the energy efficiency of methanol reformers, which is about 70% (National Research Council 1996).

Various battery types are being developed for EV applications. While the lead-acid battery is considered a most likely near-term technology, the nickel-metal hydride (Ni-MH) battery is considered to be one of the long-term battery technologies. It is implicitly assumed here that Ni-MH batteries will be used for the long-term EV technology option. On the basis of various EV energy use simulations conducted at Argonne National Laboratory, an electricity consumption rate of 0.3 kwh/mi is assumed for EVs.

Hybrid electric vehicles (HEVs) consist of on-board power units, electricity storage systems, and mechanical and/or electrical powertrain systems. HEV designs can improve vehicle fuel economy mainly in two ways. First, on-board power units can be operated at efficient engine operation spots. In this paper, on-board power units are assumed to be smaller gasoline engines. Second, the HEV electrical powertrain system can help recover braking energy. On the basis of HEV energy and emissions simulations conducted at Argonne National Laboratory, it is assumed here that HEVs powered with energy from on-board power units will achieve a fuel economy improvement of 65% over that of the benchmark gasoline car.

HEVs can be designed to operate independently of grid electricity or to connect to grid electricity. Use of grid electricity helps HEVs achieve further energy and environmental benefits. Argonne National Laboratory has estimated miles traveled with grid electricity for Ni-MH HEVs, analyzed daily VMT distribution in the United States, and calculated the percentage of VMT that can be displaced by grid electricity. Argonne's estimate shows that Ni-MH HEVs can displace about 20% of total VMT with grid electricity. Thus, in estimating GHG emissions from HEVs, it is assumed that 20% of HEV energy is from grid electricity and 80% from on-board power units. HEVs powered with grid electricity will have an electricity consumption rate of 0.3 kwh/mi, the same as for EVs.

Fuel-Cycle Paths and Key Assumptions

In this section, a fuel cycle path from primary energy recovery to fuel combustion on vehicles is specified for each technology option. GHG impacts of the AFV technologies are evaluated relative to GHG emissions of gasoline vehicles. Correspondingly, the benchmark fuel-cycle path is petroleum to gasoline. For the near-term technology options, five fuel-cycle paths are considered: NG to methanol, NG to LPG, NG to CNG, petroleum to LPG, and corn to ethanol. For the long-term technology options, six fuel-cycle paths are considered: U.S. average electricity generation and California average electricity generation for EVs and HEVs, NG to methanol for methanol-powered FCVs, NG to hydrogen and solar energy to hydrogen for hydrogen-powered FCVs, and biomass to ethanol.

Near-Term Fuel-Cycle Paths

Petroleum to Gasoline (Benchmark). This path includes crude oil recovery in oil fields, crude oil transportation and storage, crude oil refining, gasoline transportation, storage, and distribution, and gasoline combustion. Energy efficiency for each upstream stage is presented in Table 2. Using these

energy-efficiency data, GHG emissions from fuel combustion are calculated with GREET.

Some NG is produced in association with crude recovery. The so-called associated gas is in small quantity or in poor quality. It is often flared or vented into the atmosphere. If NG is flared, CO_2 emissions are calculated with NG combustion emission factors. If NG is vented, CH_4 emissions are assumed. Based on U.S. data, it is estimated here that 399 grams of NG is flared per 10^6 Btu of crude produced, and 82 grams of NG is vented per 10^6 Btu of crude produced. Besides combustion emissions, GHG emissions are generated in oil refineries by such noncombustion sources as catalyst regeneration and thermal cracking. Noncombustion CO_2 emissions are estimated to be 1,172 grams per 10^6 Btu of gasoline produced (Wang 1996).

Table 2. Energy Efficiencies of Upstream Fuel-Cycle Activities

Activity	Petroleum to gasoline	Petroleum to LPG	NG to CNG	NG to LPG	NG to methanol	NG to H_2
Primary energy recovery	98.0	98.0	94.6[a]	94.6[a]	94.6[a]	94.6[a]
Primary energy T&S	99.5	99.5	97.0	N/A[c]	N/A[c]	N/A[c]
Fuel production	85.0	93.5	95.0	96.5	65.0	68.0
Fuel T&S&D	98.5	98.0	N/A[b]	98.0	97.0	84.6[d]

Data source: Wang (1996).
[a] The efficiency includes NG recovery efficiency (97%) and NG processing efficiency (97.5%).
[b] Not applicable. CNG is produced in refueling stations.
[c] Not applicable. It is assumed here that LPG, methanol, and hydrogen are produced near NG fields.
[d] The efficiency includes gaseous hydrogen transportation efficiency (94%) and compression efficiency (90%).

Petroleum to LPG. This path includes crude recovery, crude transportation and storage, LPG production in crude refineries, and LPG transportation, storage, and distribution. Energy efficiencies for these stages are presented in Table 2.

NG to CNG. This path includes NG recovery, NG processing, NG transmission and distribution, and NG compression in CNG stations. Energy efficiencies of these stages are presented in Table 2.

Some NG is leaked during NG recovery and transmission. According to data presented by the U.S., it is estimated here that, for each 10^6 Btu of NG delivered, 65.4 grams of NG is vented or leaked to the atmosphere from NG wellheads and gathering pipelines during NG recovery, 30.9 grams during NG processing, and 182.3 grams during NG transmission and distribution. The amount of NG leaked is translated into CH_4 emissions by assuming all NG is CH_4.

During NG processing, some CO_2 is stripped from NG. According to U.S. data, the amount of CO_2 stripped is 834 grams per 10^6 Btu of NG processed.

NG to LPG. This path includes NG recovery, NG processing, LPG production, LPG transportation, storage, and distribution. Energy efficiencies for these stages are presented in Table 2.

NG to Methanol. This path includes NG recovery, NG processing, methanol production, and methanol transportation, storage, and distribution. Energy efficiencies for these stages are presented in Table 2.

Because the carbon ratio of methanol is higher than that of NG (Table 1), the process of converting 1 gram of NG to 1 gram of methanol results in a net carbon absorption. The carbon absorption rate of the methanol conversion process is estimated to be 18,081 grams of CO_2 per 10^6 Btu of methanol produced. This CO_2 value is subtracted from the CO_2 emission value calculated for NG combustion in methanol plants.

Corn to Ethanol. This path includes corn production, corn transportation, ethanol production, and ethanol transportation, storage, and distribution. GHG emissions of corn production are calculated by taking into account the amount of fuels used for farming, harvest, and corn drying, together with the amount of fertilizers and herbicides used during corn farming. Agricultural inputs for corn production are presented in Table 3.

To calculate GHG emissions for the amount of fertilizer and herbicide used for corn production, it is assumed that 43.9, 8.3, 2.5, and 272 Btu are needed to produce a gram of nitrogen fertilizer, phosphorus fertilizer, potassium fertilizer, and herbicide, respectively.

Nitrification and denitrification of nitrogen fertilizer in agriculture fields produces emissions of NO and N_2O. An emission value of 8.7 grams of N_2O per bushel of corn is calculated.

Wet milling technology is assumed for corn-to-ethanol production. In the United States, wet milling ethanol plants now account for about two-thirds of total ethanol production capacity; the remaining one-third is dry milling plants. For wet milling plants, it is assumed that a bushel of corn produces 2.5 gallons of ethanol.

Wet milling ethanol plants produce by-products that can be used for animal feed or other purposes. So total emissions from ethanol plants and from upstream corn production need to be allocated between ethanol and other by-products. There are four approaches that can be used to calculate allocation ratios: a weight approach, an energy content approach, a market value approach, and a replacement approach (Shapouri et al. 1995). The weight approach estimates allocation ratios with weight distribution between ethanol and co-products; the energy content approach, with energy content in ethanol and co-products; the market value approach, with market values of ethanol and co-products; and the replacement approach, by considering the amount of animal feed replaced by ethanol co-products that would otherwise be produced from soybeans. For wet milling ethanol

plants, an ethanol co-product credit of 52% is estimated with the weight approach, 43% with the energy content approach, 30% with the market value approach, and 19% with the replacement approach. Though the market value approach is subject to the fluctuation of market prices of ethanol and co-products, the approach, which seems reasonable for estimating corn-ethanol energy use and emissions, is used here.

Currently, corn-ethanol plants primarily use coal as the process fuel. Coal combustion generates a significant amount of CO2 emissions. In testing the sensitivity of the type of process fuels used in corn-ethanol plants to ethanol fuel-cycle GHG emissions, another case is established to assume NG as the process fuel for ethanol plants.

Table 3. Agricultural Inputs and Energy Efficiencies of Ethanol Paths

Path/Value	Corn (per bushel)	Woody biomass (per dry ton)	Herbaceous biomass (per dry ton)
Fuels for arming (Btu)	20,620	248,510	234,040
Nitrogen fertilizer (grams)	464	7,787	5,457
Phosphorus fertilizer (grams)	217	813	3,873
Potassium fertilizer (grams)	197	813	6,004
Herbicide (grams)	14.6	13.5	11.3
Transportation (Btu)	3,150	162,600	59,700
Ethanol production effic. (%)	57,214[a]	55.0[b]	57.1[b]
Ethanol T&S&D effic. (%)	97.8	97.8	97.8

[a] Btu of fuel input to corn-ethanol plants per gallon of ethanol produced.
[b] The efficiency here does not include the electricity credit in ethanol plants. The electricity credit is taken into account separately.

Long-Term Fuel-Cycle Paths

For the long-term technology options considered here, the benchmark fuel-cycle path once again is the crude-to-gasoline cycle. Methanol for FCVs is assumed to be produced from NG. Additional fuel-cycle paths for long-term technology options are presented below.

Biomass to Ethanol. This path includes biomass production, biomass transportation, ethanol production, and ethanol transportation, storage, and distribution. "Biomass" here includes both woody and herbaceous biomass. GHG emissions from biomass production are calculated in the same way as for those from corn production. Agricultural inputs for biomass production are

presented in Table 3.

Nitrification and denitrification of nitrogen fertilizer in biomass farms produces emissions of NO and N_2O. Emission values of 43.8 and 85.7 grams of N_2O are estimated, respectively, for each dry ton of woody and herbaceous biomass produced.

In this study, it is assumed that biomass is burned in biomass-to-ethanol plants to provide heat needed for ethanol production. While combustion of biomass undoubtedly produces CO_2 emissions, these emissions come from the atmosphere through the process of photosynthesis during biomass growth. Thus, CO_2 emissions from biomass combustion are treated as being zero here. For the same reason, CO_2 emissions from ethanol combustion by ethanol-powered vehicles also are treated as being zero.

Combustion of biomass in biomass-to-ethanol plants through cogeneration facilities generates electricity and also provides the heat required for ethanol production. Credits amounting to 1.11 and 0.67 kwh of electricity per gallon of ethanol produced are estimated for woody and herbaceous biomass ethanol plants, respectively (Wang 1996). The electricity generated is assumed to be exported to the electric grid. Emissions credits for the generated electricity are calculated in GREET by taking into account the amount of electricity generated and the average emissions associated with electricity generation in electric utility systems.

NG to H_2. Although both liquid and gaseous H_2 can be used for H_2-powered FCVs, gaseous H_2 is assumed here. Liquefaction of H_2 poses additional energy loss and emissions issues. Transportation and storage of liquid H_2 can be expensive. For gaseous H_2, the path from NG to H_2 includes NG recovery, NG processing, H_2 production, H_2 transportation and storage, and H_2 compression at service stations. Energy efficiencies for these stages are presented in Table 2.

Because of the elimination of carbon in H_2, the conversion of NG to H_2 produces excess CO_2 emissions. It is estimated here that the conversion process produces CO_2 at a rate of 48,376 grams per 10^6 Btu of H_2 produced. Two cases are simulated here to address the issue of CO_2 emissions from H_2 plants. One case assumes that all the CO_2 produced from steam reforming is emitted into the atmosphere. The other case assumes that 90% of the amount of CO_2 produced is sequestered into such places as used NG wells (see Williams 1996).

Solar Energy to H_2. Production of H_2 from solar energy via water electrolysis offers great energy and environmental benefits. This use of solar energy enables the transportation sector to use a practically unlimited energy source. It has been argued that, in the long run, H_2 from solar energy is an ultimate energy source for the transportation sector (Delucchi 1992), although much needs to be done to reduce the cost of solar H_2 technologies.

It is assumed here that H_2 is produced in centralized facilities in such regions as the Southwestern United States where solar energy is abundant. The produced H_2 is compressed moderately (to about 100 psi) and then transported to H_2 service stations via pipelines. In service stations, gaseous H_2 is

compressed to 5,000-6,000 psi and refueled to H_2-powered FCVs. It is further assumed that electricity is used for H_2 compression and transportation. The U.S. average electricity generation is used here to estimate GHG emissions of the electricity used for H_2 transportation and compression. It is estimated that the energy efficiency of gaseous H_2 transportation via pipeline is 94% and that of H_2 compression in service stations is 90%. Fossil energy use for H_2 production from solar energy is negligible, and is ignored here.

Electricity Generation. Grid electricity is used for EVs and HEVs. Emissions associated with grid electricity are determined very much by electric generation mix. Many studies have been conducted to identify the so-called marginal electric generation mix for providing electricity for EVs. The results depend on the electric utility systems involved, how much and what types of new electric capacity are assumed to be added in the future, the amount of electricity needed by EVs, and many other factors. Rather than "guesstimating" future electric marginal mix, this paper uses the future average electric mix to provide some results on EV and HEV emissions. To cover a range of electric generation mixes, two distinctly different generation mixes for EVs are selected. The first mix is the U.S. electric generation mix, and the second is the California generation mix (Table 4).

Table 4. Electricity Generation Mix in the U.S. and in California (%)

	Coal	Oil	NG	Nuclear	Others[a]
U.S. 2005[b]	50.9	3.4	14.9	18.9	11.9
U.S. 2015[c]	50.3	4.2	18.0	15.5	12.0
California[d]	7.0	0.2	30.6	14.1	48.1

[a] Others include hydropower, geothermal energy, wind, etc.; they are assumed to have zero GHG emissions.
[b] This generation mix is used to estimate GHG emissions of electricity generation in 2005 for the near-term technology options. Values based on information from EIA (1995).
[c] This generation mix is used to estimate GHG emissions of electricity generation in 2015 for the long-term technology options, as well as for EVs and HEVs under the U.S. generation mix scenario. Values based on information from EIA (1995); 2010 data are adopted here for 2015 data.
[d] This generation mix is used to estimate GHG emissions of electricity generation in 2015 for EVs and HEVs under the California generation mix scenario. Values based on information from California department of Finance (1996).

Results

Figure 2 presents CO_2-equivalent GHG emissions for both near-term and long-term technologies. Quantitative results for these technologies are presented in Tables 5 and 6. Here, GHG emissions are the total of CO_2, CH_4, and N_2O weighted with their global warming potentials. According to Intergovernmental Panel on Climate Change (IPCC), global warming potential is 1 for CO_2, 21 for CH_4, and 310 for N_2O (IPCC 1995). Near-term AFV technologies offer small to moderate GHG benefits. In fact, GHG emissions from CNG are actually 8% higher than those from baseline gasoline. E85 with coal as the process fuel in ethanol plants can reduce GHG emissions by 15%.

If NG is used as the process fuel for ethanol plants, GHG emission reductions by E85 are doubled to 30%. LPG produced from both NG and crude results in about a 10% reduction in GHG emissions. M85 has GHG emissions similar to those from gasoline. Except for E85, vehicle operations account for more fuel-cycle emissions than do upstream activities. For E85, CO_2 emissions from ethanol combustion are treated as being zero, because the carbon burned is the carbon obtained from the atmosphere during corn growth. It would be possible to assign a carbon absorption rate (a negative CO_2 value) for corn growth and use the actual CO_2 emissions from ethanol combustion. This is purely an accounting issue, which does not affect fuel-cycle GHG emissions at all.

While CO_2 emissions dominate total GHG emissions, N_2O emissions for corn-ethanol (as a result of nitrification and denitrification of nitrogen fertilizer) and CH_4 emissions during NG production and distribution for NG-based fuels (i.e., CNG, LPG, and methanol) also account for a significant amount of total GHG emissions. The CH_4 emissions are partly responsible for the increased GHG emissions by CNG.

The long-term technologies have great potential for reducing GHG emissions. Relative to the 2010 baseline gasoline vehicle, these technologies can reduce GHG emissions by 25 to 85%. Two renewable-energy-based fuels (hydrogen from solar energy and biomass ethanol) achieve over 80% reductions in GHG emissions. The magnitude of GHG emission reductions by EVs depends very much on the electric generation mix. In the case of the U.S. electric generation mix, where more than 50% of electricity is generated from coal, EVs achieve about a 32% reduction in GHG emissions. With the California generation mix, where nearly 50% of electricity is produced from such renewable sources as hydropower, wind, and solar energy, EVs can achieve more than a 70% reduction in GHG emissions. Grid-connected HEVs with California generation mix achieve about a 45% reduction in GHG emissions because of fuel economy improvements associated with the on-board engines and use of grid electricity. With the U.S. generation mix, HEV reduces GHG emissions by 35%.

Among the three cases involving hydrogen FCVs, solar hydrogen achieves the largest GHG emission reduction (about 85%). With no CO_2 sequestered from hydrogen production, NG-hydrogen FCVs reduce GHG emissions by 39%. Sequestration of CO_2 in hydrogen production results in an additional 24% reduction in GHG emissions by hydrogen FCVs. Methanol FCVs achieve a 24% reduction in GHG emissions; the small value of the reduction is caused by methanol being a carbon-based fuel and by efficiency losses due to on-board reforming of methanol to hydrogen.

Conclusions

Different AFV technologies can have significantly different impacts on GHG emissions from motor vehicles. The four near-term AFV technology options (vehicles fueled with M85, E85, CNG, and LPG) offer small to moderate GHG benefits. Nonetheless, these technologies have been promoted and used for reducing transportation petroleum use and urban air pollution, as well as for reducing GHG emissions. These technologies should continue to be used for pursuing these other benefits.

The long-term AFV technology options (EVs, HEVs, vehicles fueled with biomass ethanol, and FCVs) have great potential for reducing GHG emissions. This is especially true of those technologies that use renewable energy, such as biomass and solar energy. At present, these technologies are either in the prototype stage or still under development. Extensive R&D efforts are needed to develop these technologies in order for them to compete successfully with conventional gasoline vehicle technology.

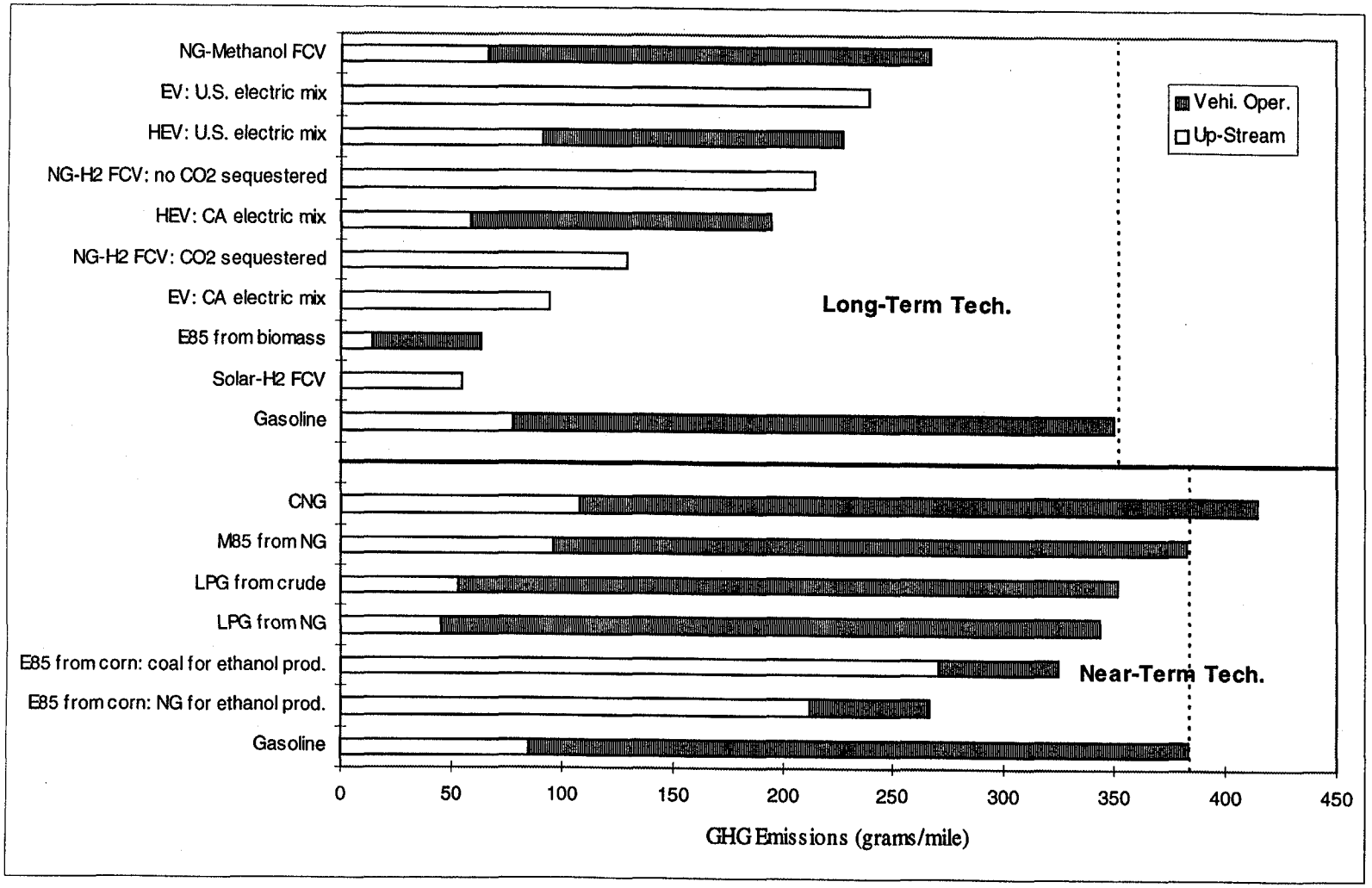


Figure 2. Per-Mile GHG Emissions: Near-Term and Long-Term AFV Technology Options

Table 5. GHG Emissions of Alternative-Fueled Vehicles: Near-Term Technologies (gms/mi.)

		CO_2	CH_4	N_2O	GHGs[b]
Gasoline	Up-stream	76.2	0.356	0.004	85.0
	Vehi. Oper.	294.9	0.076	0.005	298.0
	Total	371.1	0.432	0.009	383.1
E85 from corn: NG for ethanol production	Up-stream	172.9	0.205	0.112	211.9
	Vehi. Oper.	51.7[a]	0.049	0.005	54.3
	Total	224.6	0.255	0.117	266.3
E85 from corn: coal for ethanol production	Up-stream	233.0	0.107	0.113	270.4
	Vehi. Oper.	51.7[a]	0.049	0.005	54.3
	Total	284.7	0.157	0.118	324.7
LPG from NG	Up-stream	35.5	0.429	0.001	44.9
	Vehi. Oper.	295.1	0.076	0.005	298.3
	Total	330.6	0.505	0.006	343.2
LPG from crude	Up-stream	44.5	0.358	0.003	53.0
	Vehi. Oper.	295.1	0.076	0.005	298.3
	Total	339.7	0.434	0.008	351.3
M85 from NG	Up-stream	84.5	0.507	0.004	96.4
	Vehi. Oper.	283.3	0.049	0.005	285.8
	Total	367.8	0.556	0.009	382.2
CNG	Up-stream	74.9	1.324	0.018	108.2
	Vehi. Oper.	272.5	1.520	0.005	306.0
	Total	347.4	2.844	0.023	414.2

[a] CO_2 emissions from ethanol combustion by ethanol vehicles are treated as being zero here, since the carbon contained in ethanol is sequestered from the atmosphere through corn growth. Alternatively, a CO_2 sequestration credit could be assigned to corn growth and CO_2 emissions of ethanol combustion could be used. Both methods should produce the same total amount of CO_2 emissions for the complete cycle from corn growth to ethanol combustion.

[b] GHG emissions are calculated as $CO_2 + 21 \times CH_4 + 310 \times N_2O$. 21 is the global warming potential of CH_4 and 310 is that of N_2O.

Table 6. GHG Emissions of Alternative-Fueled Vehicles: Long-Term Technologies: (gms/mi.)

		CO_2	CH_4	N_2O	GHGs[b]
Gasoline	Up-stream	70.1	0.327	0.002	77.7
	Vehi. Oper.	269.3	0.076	0.005	272.4
	Total	339.4	0.403	0.007	350.1
Solar H_2 FCV	Up-stream	48.2	0.219	0.008	55.2
	Vehi. Oper.	0.0	0.000	0.000	0.0
	Total	48.2	0.219	0.008	55.2
E85 from biomass	Up-stream	7.6	0.075	0.018	14.7
	Vehi. Oper.	46.6[a]	0.049	0.005	49.2
	Total	54.2	0.125	0.023	63.9
EV: California electric mix	Up-stream	85.9	0.308	0.007	94.5
	Vehi. Oper.	0.0	0.000	0.000	0.0
	Total	85.9	0.308	0.007	94.5
NG-H_2 FCV: CO_2 sequestered	Up-stream	120.5	0.296	0.009	129.6
	Vehi. Oper.	0.0	0.000	0.000	0.0
	Total	120.5	0.296	0.009	129.6
HEV: California electric mix	Up-stream	53.5	0.224	0.002	58.9
	Vehi. Oper.	133.6	0.049	0.003	135.6
	Total	187.1	0.273	0.005	194.5
NG-H_2 FCV: no CO_2 sequestered	Up-stream	205.3	0.296	0.009	214.3
	Vehi. Oper.	0.0	0.000	0.000	0.0
	Total	205.3	0.296	0.009	214.3
HEV: U.S. electric mix	Up-stream	83.0	0.263	0.009	91.5
	Vehi. Oper.	133.6	0.049	0.003	135.6
	Total	216.6	0.312	0.013	227.1
EV: U.S. electric mix	Up-stream	216.1	0.501	0.040	239.0
	Vehi. Oper.	0.0	0.000	0.000	0.0
	Total	216.1	0.501	0.040	239.0
NG-methanol FCV	Up-stream	58.2	0.386	0.002	67.0
	Vehi. Oper.	199.0	0.000	0.004	200.1
	Total	257.2	0.386	0.006	267.0

[a] See footnote a of Table 5.
[b] See footnote b of Table 5.

Acknowledgments

This work was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, Office of Technology Utilization, under contract W-31-109-Eng-38. The author is grateful to Floyd Bennett for editing the paper. The author is solely responsible for the content of this paper.

References

California Department of Finance. 1996. *1996 California Statistics Abstract*, Sacramento, Calif.

Canadian Gas Association. 1995. *1990 Air Emissions Inventory for the Canadian Natural Gas Industry*, Canadian Gas Association, North York, Ontario, Canada, March.

Delucchi, M.A. 1992. *Hydrogen Fuel-Cell Vehicles*, University of California at Davis, Institute of Transportation Studies, research report # UCD-ITS-RR-92-14, Davis, Calif., Sept. 1.

EIA — see Energy Information Administration.

Energy Information Administration. 1994. *Energy Use and Carbon Emissions: Some International Comparisons*, Energy Information Administration, Office of Energy Markets and End Use, U.S. Department of Energy, DOE/EIA-0579, Washington, D.C., March.

Energy Information Administration. 1995. *Alternatives to Transitional Transportation Fuels 1993*, Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternative Fuels, U.S. Department of Energy, DOE/EIA-0585(93), Washington, D.C., Jan.

Energy Information Administration. 1997. *1997 Annual Energy Outlook, Supporting Document*, Energy Information Administration, U.S. Department of Energy, Washington, D.C., Jan.

Intergovernmental Panel on Climate Change. 1995. *Climate Change 1995: Impacts, Adaptations, and Mitigation, Summary for Policymakers*, Paris, France, Oct.

National Research Council. 1996. *Review of the Research Program of the Partnership for a New Generation of Vehicles, Second Report*, National Academy Press, Washington, D.C.

Shapouri, H., J.A. Duffield, and M.S. Graoski. 1995. *Estimating the Net Energy Balance of Corn Ethanol*, U.S. Department of Agriculture, Economic Research Services, report No. 721, Washington, D.C., July.

Wang, M.Q. 1996. *GREET 1.0 — Transportation Fuel Cycles Model: Methodology and Use*, Center for Transportation Research, Argonne National Laboratory, ANL/ESD-33, Argonne, Ill.,

June.

Williams, R.H. 1996. *Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated CO_2*, Center for Energy and Environmental Studies, Princeton University, PU/CEES report No. 295, Princeton, NJ, Jan.