# WELL-TO-WHEELS ANALYSIS OF FUEL-CELL VEHICLE/FUEL SYSTEMS

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## 1. INTRODUCTION AND APPROACH

Major automobile companies worldwide are undertaking vigorous research and development efforts aimed at developing fuel-cell vehicles (FCVs). Proton membrane exchange (PEM)-based FCVs require hydrogen ($H_2$) as the fuel-cell (FC) fuel. Because production and distribution infrastructure for $H_2$ off board FCVs as a transportation fuel does not exist yet, researchers are developing FCVs that can use hydrocarbon fuels, such as methanol (MeOH) and gasoline, for onboard production of $H_2$ via fuel processors.

Direct $H_2$ FCVs have no vehicular emissions, while FCVs powered by hydrocarbon fuels have near-zero emissions of criteria pollutants and some carbon dioxide ($CO_2$) emissions. However, production of $H_2$ can generate a large amount of emissions and suffer significant energy losses. A complete evaluation of the energy and emission impacts of FCVs requires an analysis of energy use and emissions during all stages, from energy feedstock wells to vehicle wheels — a so-called "well-to-wheels" (WTW) analysis.

Since 1995, with funding from the U.S. Department of Energy's (DOE's) Office of Transportation Technologies (OTT), Argonne National Laboratory has been developing the *G*reenhouse gases, *R*egulated *E*missions, and *E*nergy use in *T*ransportation (GREET) model for estimating WTW energy use and emissions associated with transportation fuels and advanced vehicle technologies. The GREET model, including its current version (GREET 1.6) (Wang 2001), and associated documents are posted at Argonne's GREET website (http://greet.anl.gov). Argonne has applied the GREET model to analyze WTW energy and emission impacts of various transportation fuels and vehicle technologies (Wang and Huang 1999; General Motors Corporation et al. 2001a,b, c). Various other organizations — including automobile companies, energy companies, government agencies, universities, and other institutions in North America, Europe, and Asia — are using the GREET model for their evaluations of vehicle/fuel systems.

This paper focuses on FCVs powered by several transportation fuels. Gasoline vehicles (GVs) equipped with internal combustion engines (ICEs) are the baseline technology to which FCVs are compared. Table 1 lists the 13 fuel pathways included in this study. Petroleum-to-gasoline (with 30-ppm sulfur [S] content) is the baseline fuel pathway for GVs.

Table 1. FCV Fuel Pathways Included in This Study

| Feedstock | Fuel | Comment |
|---|---|---|
| Petroleum | Gasoline | Low-sulfur (LS) gasoline, with a 30-ppm S content, is used to fuel baseline GVs |
| NG | Central $G.H_2$ | $G.H_2$ is produced in central plants, transported by pipeline to refueling stations, and compressed to about 6,000 psi |
| NG | Station $G.H_2$ | NG is transported by pipeline to refueling stations; $G.H_2$ is produced at stations and compressed to about 6,000 psi |
| NG | Central $L.H_2$ | $L.H_2$ is produced in central plants and transported to refueling stations |
| NG | Station $L.H_2$ | NG is transported by pipeline to refueling stations; $L.H_2$ is produced there |
| U.S. average electricity | $G.H_2$ via electrolysis | $G.H_2$ is produced at refueling stations and compressed to about 6,000 psi |
| U.S. average electricity | $L.H_2$ via electrolysis | $L.H_2$ is produced at refueling stations |
| Renewable electricity | $G.H_2$ via electrolysis | $G.H_2$ is produced at refueling stations and compressed to about 6,000 psi |
| Solar energy | $G.H_2$ via photovoltaic and electrolysis | $G.H_2$ is produced in central plants, transported by pipeline to refueling stations, and compressed to about 6,000 psi |
| NG | Methanol | Methanol is produced in central plants and transported to refueling stations |
| Petroleum | Gasoline | Gasoline is a fuel-cell fuel with a S content below 10 ppm |
| Petroleum | Naphtha | Naphtha is a fuel-cell fuel with a S content close to 0 ppm |
| NG | Naphtha | Naphtha, together with middle distillates, is produced via the Fischer-Tropsch (FT) process and has a zero S content |

Gaseous $H_2$ ($G.H_2$) for FCV applications needs to be compressed to about 6,000 psi in order to store enough energy for a reasonable FCV driving range. FCVs fueled by liquid $H_2$ ($L.H_2$) can have a longer driving range than those fueled with $G.H_2$, but $L.H_2$ storage requires strict heat insulation for $L.H_2$ tanks and can suffer from boil-off losses.

At present, $H_2$ is primarily produced from natural gas (NG) via steam methane reforming (SMR), a commercially mature technology. Transportation of massive amounts of $H_2$ from central plants to refueling stations for motor vehicle applications can require a significant capital investment. One option to avoid the need for a formidable, costly $H_2$ transportation infrastructure is to transport NG to refueling stations via pipelines and produce $H_2$ at the refueling stations. The station production option is included in this study.

A limited amount of $H_2$ is currently produced from electricity by electrolyzing water. Although mass-scale $H_2$ production by this method may not be economically feasible in many regions where electricity costs are high, electrolysis $H_2$ production can be carried out at refueling stations to avoid the investment required for $H_2$ transportation infrastructure. In the future, $H_2$ produced via electrolysis could be used to fuel FCVs in remote, less populated areas where adequate $H_2$ production and transportation infrastructure is lacking. Because the source for electricity generation is a key factor in determining energy and emission effects of electrolysis $H_2$, we analyzed two cases for the electrolysis $H_2$ production option: average U.S. electricity (about 54% of which is generated from coal) and electricity generation from renewable sources such as hydropower, wind, solar energy, and nuclear energy (although some may argue that nuclear energy is not really a renewable energy source, energy and emission effects of nuclear power are similar to those of renewable electricity. Thus, nuclear power is grouped together with renewable electricity in this paper).

We included G.$H_2$ produced by means of photovoltaic technology in regions where solar energy is abundant (such as the U.S. Southwest region). The transportation logistics for this pathway are similar to those for centralized $H_2$ production pathways. That is, $H_2$ is transported via pipelines from production sites to refueling stations, where it is compressed.

We address pathways for three hydrocarbon fuels — methanol, gasoline, and naphtha — in this paper. Methanol is currently produced from NG at large scales. Gasoline for FCV applications may require low- or zero-sulfur content. We assume 10-ppm-S gasoline for FCV applications. Even with this level of sulfur, desulfurization may be needed onboard FCVs before gasoline enters the fuel processor. Naphtha has a low octane number and is not an attractive gasoline blendstock. However, naphtha could be used as a fuel-cell fuel because octane number does not matter in fuel-cell applications. Naphtha produced in petroleum refineries (crude naphtha) is currently a petrochemical feedstock. With moderate desulfurization, crude naphtha with near-zero sulfur content could be used as a fuel-cell fuel. There has also been heightened interest in Fischer-Tropsch (FT) diesel production from NG in the past several years. Besides diesel, FT plants also produce naphtha. Because FT naphtha could also be used as a fuel-cell fuel, we include both crude and FT naphtha in our analysis.

One drawback of a WTW analysis is that it does not address the technology status of different vehicle and fuel systems. Often, technologies included in a study are at different stages of commercial readiness. Without addressing the costs and commercial readiness associated with different technologies, WTW analyses may give readers the false impression that the evaluated technologies are at the same level of cost competitiveness and market readiness. Readers should keep in mind that different technologies may be at different stages of commercial readiness.

## 2. KEY ASSUMPTIONS

While WTW methodologies are generally similar among studies, studies differ in terms of scope, timeframe, and geographic regions covered. These differences can result in different parametric assumptions regarding energy efficiencies and emissions for WTW stages. This section presents key parametric assumptions used in this study.

We used the advanced feature in GREET 1.6 to conduct stochastic simulations, in which the GREET model can generate energy and emission results with probability distribution functions. To conduct stochastic simulations with GREET 1.6, we established probability-based input assumptions, discussed below.

### 2.1 WELL-TO-PUMP ASSUMPTIONS

Details regarding the assumptions described in Sections 2.1.1 and 2.1.2 are documented in a study that Argonne completed for General Motors (General Motors Corporation et al. 2001c).

### 2.1.1 Petroleum to GV Gasoline, FCV Gasoline, and FCV Naphtha

Beginning in 2004, the U.S. Environmental Protection Agency (EPA) will require production of gasoline with an average sulfur content of 30 ppm (we used this as the baseline gasoline for our study). Because sulfur can poison the catalysts used in fuel processors, FCVs may require much lower (or even zero) sulfur content for gasoline. We assumed a sulfur content of less than 10 ppm for fuel-cell gasoline. Even with this lower sulfur level, FCVs may still need some onboard desulfurization measures to remove sulfur from the gasoline.

Petroleum refineries produce naphtha, which could be an FCV fuel candidate. We assumed that the sulfur content of naphtha will be reduced to below 10 ppm. Table 2 presents energy efficiencies for the key stages of the petroleum-based fuels in our study. We assumed the normal distribution curve for the parameters except as noted.

Table 2. Energy Efficiencies for Fell-Cell Fuel Pathway Stages (Based on Low Heating Values)

| Stage | Energy Efficiency (%) | | |
|---|---|---|---|
| | P20[a] | P50[a] | P80[a] |
| Petroleum recovery[b] | 96.0 | 98.0 | 99.0 |
| Petroleum refining to 30-ppm-S gasoline | 83.0 | 84.5 | 86.0 |
| Petroleum refining to 10-ppm-S gasoline | 82.5 | 84.0 | 85.5 |
| Petroleum refining to 10-ppm-S naphtha | 89.0 | 91.0 | 93.0 |
| NG recovery | 96.0 | 97.5 | 99.0 |
| NG processing | 96.0 | 97.5 | 99.0 |
| G.$H_2$ production at central plants | 68.0 | 71.5 | 75.0 |
| $H_2$ liquefaction at central plants | 65.0 | 71.0 | 77.0 |
| G.$H_2$ production at refueling stations | 62.0 | 67.0 | 72.0 |
| $H_2$ liquefaction at refueling stations | 60.0 | 66.0 | 72.0 |
| G.$H_2$ compression by NG compressors[b] | 83.0 | 85.5 | 88.0 |
| G.$H_2$ compression by electric compressors[b] | 91.0 | 93.3 | 96.3 |
| Methanol production in central plants | 65.0 | 67.5 | 71.0 |
| FT naphtha production | 61.0 | 63.0 | 65.0 |
| Oil-, NG-, and coal-fired power plants with steam boilers | 32.5 | 35.3 | 38.0 |
| NG-fired power plants with combined-cycle turbines[b] | 50.0 | 55.0 | 60.0 |
| Coal-fired power plants with advanced technologies | 38.0 | 41.5 | 45.0 |
| Electrolysis $H_2$ production at refueling stations | 67.0 | 71.5 | 76.0 |

[a] P20 — probability of 20%; P50 — probability of 50%; P80 — probability of 80%.
[b] A triangle distribution curve was assumed.

### 2.1.2 Natural Gas to Hydrogen, Methanol, and Naphtha

This study includes six NG-based pathways producing $H_2$, methanol, and naphtha (see Table 1). In our past studies, we included both North American (NA) NG and non-North American (NNA) NG to produce these fuels. Here, we included one source of NG for each fuel pathway. For G.$H_2$, we assumed that NA NG is the feedstock. For liquid fuels (L.$H_2$, methanol, and naphtha), we assumed that NNA NG is the feedstock. Some experts predict that the amount of NA NG available for transportation use will be limited. Thus, liquid fuels could be produced outside of North America and transported to North America for use. However, if gaseous fuels are produced from NNA NG, the NG will have to be liquefied and transported to North America. The additional liquefaction step will certainly add additional costs, energy use, and emissions to the pathways, possibly making them less attractive. For L.$H_2$ produced in refueling stations, we assumed that NA NG will be the feedstock source.

Table 2 presents energy efficiency assumptions for the six NG-based pathways. All of these pathways will require NG recovery and processing. Plants that produce $H_2$, methanol, and FT naphtha can be designed to produce steam and/or electricity. If steam and/or electricity are co-produced with these fuels, the overall plant energy efficiency can be improved. In our past studies, we evaluated energy and emission effects of plants with co-produced steam and/or electricity. In this paper, we evaluated plant designs that do not include steam and/or electricity export.

Liquid $H_2$ pathways suffer two major energy losses: G.$H_2$ production and $H_2$ liquefaction. In addition, L.$H_2$ is subject to boil-off losses. If L.$H_2$ is stored for a long period of time before use, boil-off losses can be significant. Because of these efficiency penalties, L.$H_2$ pathways generally consume larger amounts of energy and produce more emissions than G.$H_2$ pathways.

### 2.1.3 Electrolysis Hydrogen

$H_2$ can be produced by electrolysis of water by means of electricity at refueling stations. Because the transmission and distribution infrastructure for electricity is already in place throughout most countries, this production option helps avoid long-distance transportation of $H_2$.

Because the energy sources used for electricity generation are the most important factor in determining energy use and greenhouse gas (GHG) emissions of electrolysis $H_2$, we analyzed two cases of electricity generation for electrolysis $H_2$ production: U.S. average electricity generation (54% coal; 15% NG; 1% oil; 18% nuclear; and 12% hydropower, geothermal energy, and other sources) and electricity generation from renewable energy sources.

We also include $H_2$ production from solar energy via photovoltaic panels. For this pathway, photovoltaic panels collect solar energy and convert it into electricity. The electricity is then used to produce $H_2$ via electrolysis. To generate enough electricity for $H_2$ production, a large area of photovoltaic panels and abundant solar energy are necessary. These requirements prevent refueling station $H_2$ production from solar energy. We assumed that $H_2$ production from solar energy will occur in regions such as the American Southwest. $H_2$ produced there will be transported to refueling stations.

Table 2 presents our assumptions regarding electrolysis $H_2$ production at refueling stations. For electricity delivered to refueling stations, we used an electric transmission and distribution loss of 8%, the U.S. average loss. In our calculations, we used a conversion efficiency of 100% from renewable energy sources to electricity because, for renewable sources, resource consumption is not a concern.

## 2.2 PUMP-TO-WHEEL ASSUMPTIONS

The key pump-to-wheels parameter that determines WTW energy use and GHG emissions associated with vehicle/fuel systems is vehicle fuel economy (in miles per gallon [mpg]). Models are available for predicting the fuel economy of conventional vehicle technologies. Their fuel economy predictions are generally reliable. Recently, researchers have made efforts to develop modeling capabilities to predict the fuel economy of advanced vehicle technologies such as FCVs (General Motors Corporation et al. 2001b; Kumar et al. 2000; Ogden et al. 1999; Thomas et al. 1998; Thomas 1999; and Weiss et al. 2000). Figure 1 graphically shows the range of FCV fuel economy ratios to baseline GV fuel economy summarized from these studies. The number next to the name of each vehicle type in the chart represents the number of studies that simulated the given type. The range of fuel economy ratios for a given vehicle type reflect technology uncertainties, vehicle design options, and performance attributes.

On the basis of these completed studies, we developed fuel economy assumptions for our study of FCVs; these assumptions are listed in Table 3.

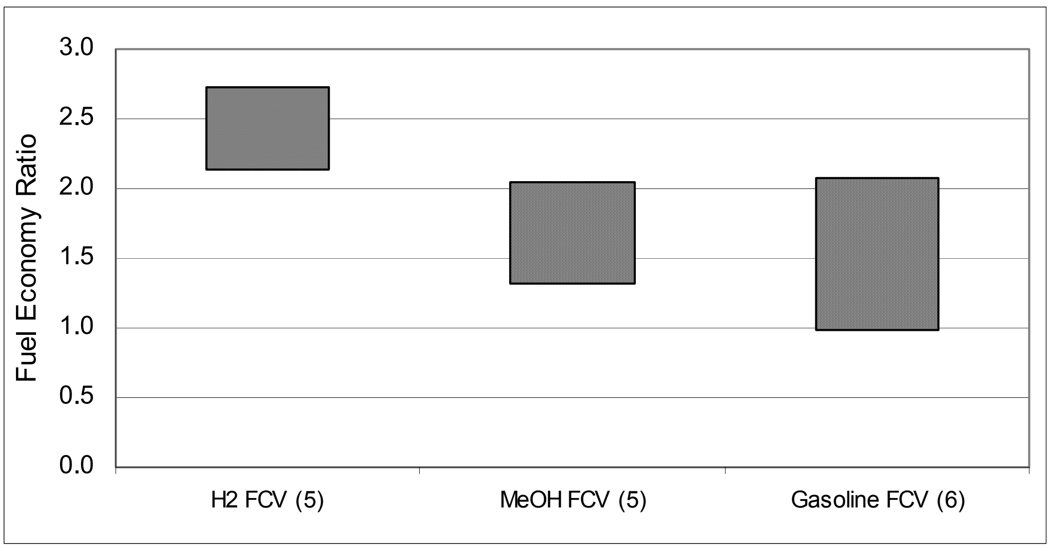


Figure 1. Fuel Economy Ratios of FCVs to Baseline GVs (the number next to each vehicle type represents the number of studies for the type)

Table 3. Distribution Functions for FCV Fuel Economy Ratios (relative to GV fuel economy, the Weibull distribution curve is assumed)[a]

| Vehicle Type | Low-Bound Value | P50 Value | P95 Value |
|---|---|---|---|
| Baseline GV fuel economy (mpg) | 22.0 | 27.0 | 33.0 |
| $H_2$ FCV | 2.10 | 2.35 | 2.60 |
| Methanol FCV | 1.30 | 1.60 | 1.80 |
| Gasoline and naphtha FCV | 1.00 | 1.50 | 1.70 |

[a] The fuel economy of baseline GVs and the fuel economy ratios of FCVs are for a mid-size car. The fuel economy values are for the 55/45 combined cycle with on-road adjustments to reflect fuel economy deterioration from laboratory testing to on-road driving.

## 3. RESULTS

We used the GREET model to conduct stochastic simulations of WTW energy use and GHG emissions for the vehicle/fuel systems included in this study. GREET generates results for a given output item with a probability distribution.

### 3.1 WELL-TO-PUMP ENERGY EFFICIENCIES

Figure 2 presents well-to-pump energy efficiencies for 10 fuel pathways. These efficiencies are calculated from the energy losses that occur along the pathway from primary energy feedstocks to fuels available at fuel pumps in refueling stations. The baseline crude-to-reformulated gasoline (RFG) pathway has an efficiency of 80%. The energy efficiency of crude naphtha is higher than the gasoline efficiency. This means that even if vehicles using crude naphtha achieve the same mpg as baseline GVs, these vehicles will have better WTW energy efficiencies than GVs. On the other hand, the remaining eight fuel pathways have lower well-to-pump efficiencies than gasoline. Vehicles using these fuels must have higher mpg values in order to achieve overall WTW energy efficiency gains over baseline GVs. The least efficient pathways are $G.H_2$ and $L.H_2$ produced via electrolysis with average U.S. electricity generation. The electrolysis $L.H_2$ well-to-pump efficiency is about 20% — one-fourth the efficiency of RFG. This finding suggests that FCVs fueled with $L.H_2$ made via this pathway need to have fuel economy at least four times that of baseline GVs for FCVs to achieve the same level of overall WTW energy efficiency. Similarly, FCVs fueled with electrolysis $G.H_2$ need to achieve a fuel economy level at least 2.7 times that of GVs. This chart clearly shows that different fuel pathways are subject to different well-to-pump energy losses.

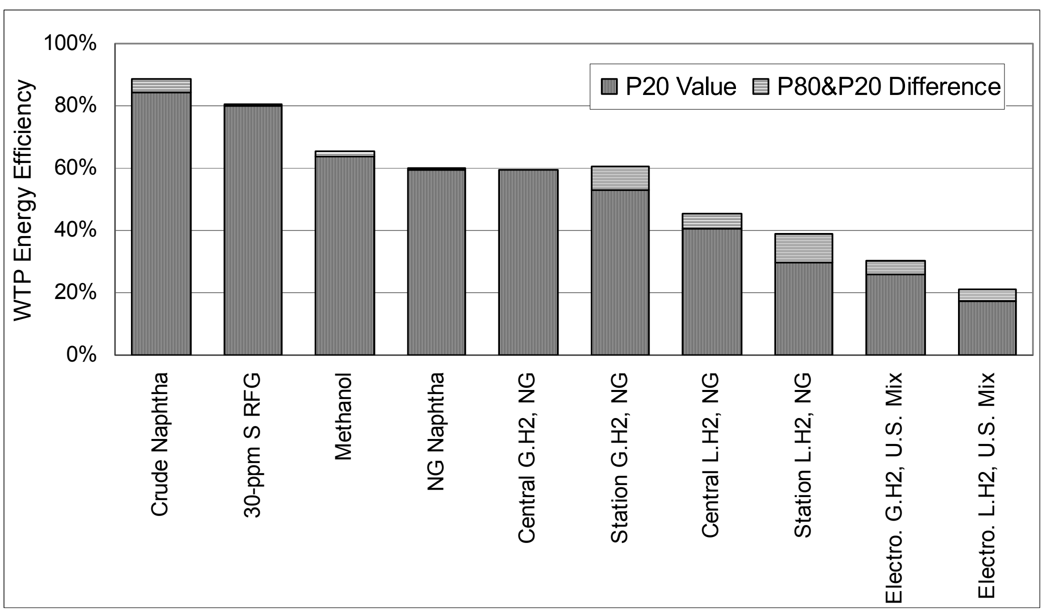


Figure 2. Well-to-Pump Energy Efficiencies of Transportation Fuels

### 3.2 WELL-TO-WHEEL TOTAL ENERGY USE

Figure 3 presents per-mile WTW total energy use for FCVs and baseline GVs. These energy uses are based on well-to-pump efficiencies (Figure 2) and relative fuel economy (Table 3). Except for NG naphtha, FCVs powered by the other three hydrocarbon fuels have lower total energy use than baseline GVs. Of the four NG-based $H_2$ options, $G.H_2$ and central $L.H_2$ achieve lower per-mile energy, but station $L.H_2$ could increase total energy use. Of the four electrolysis $H_2$ options, $G.H_2$

and L.$H_2$ based on U.S. average electricity generation increase per-mile total energy use. The increases are caused by significant energy losses during the well-to-pump stages for these fuels. The well-to-pump energy losses are so large that even the improved mpg of FCVs is not enough to offset the losses for these options. Figure 3 shows that even efficient FCVs may not achieve energy benefits if inefficient fuel pathways are used to provide fuels for them.

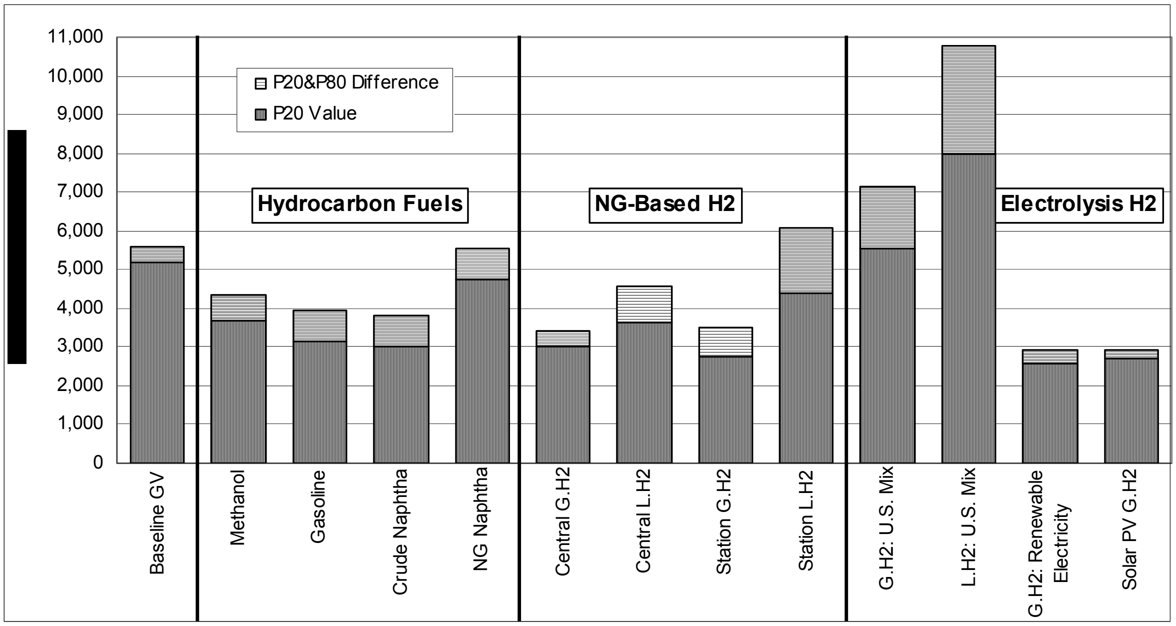


Figure 3. Per-Mile Well-to-Wheel Total Energy Use for Baseline GVs and FCVs

### 3.3 WELL-TO-WHEEL FOSSIL ENERGY USE

Figure 4 shows per-mile WTW fossil energy use (petroleum, NG, and coal) for FCVs and GVs. Fossil energy use differs significantly from total energy use for the two electrolysis $H_2$ options based on renewable electricity and solar photovoltaic. These fuel pathways demonstrate large reductions in fossil energy use, relative to RFG-fueled GVs. The difference between total energy use and fossil energy use demonstrates the need for taking into account the type, as well as the number, of energy sources used in producing transportation fuels.

### 3.4 WELL-TO-WHEEL GREENHOUSE GAS EMISSIONS

Figure 5 shows per-mile WTW GHG emissions for FCVs. GHG emissions here include carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). The three gases are combined with their global warming potentials (1 for $CO_2$, 21 for $CH_4$, and 310 for $N_2O$). Except for FCVs fueled with G.$H_2$ and L.$H_2$ produced with average U.S. electricity, all other FCV options reduce GHG emissions. The two renewable fuel options (G.$H_2$ from renewable electricity and solar photovoltaic panels) almost eliminate GHG emissions.

## 4. CONCLUSIONS

Of the vehicle/fuel systems evaluated in this study, FCVs fueled with $H_2$ produced via electrolysis consume more energy than do baseline GVs. Other FCV options achieve significant energy reduction benefits. All FCV options, except FCVs fueled by $H_2$ produced from average U.S. electricity, help reduce GHG emissions significantly. If the goal of introducing FCVs is to achieve significant energy and GHG emissions reduction benefits, the pathways used to produce fuels for FCVs must be carefully examined and selected.

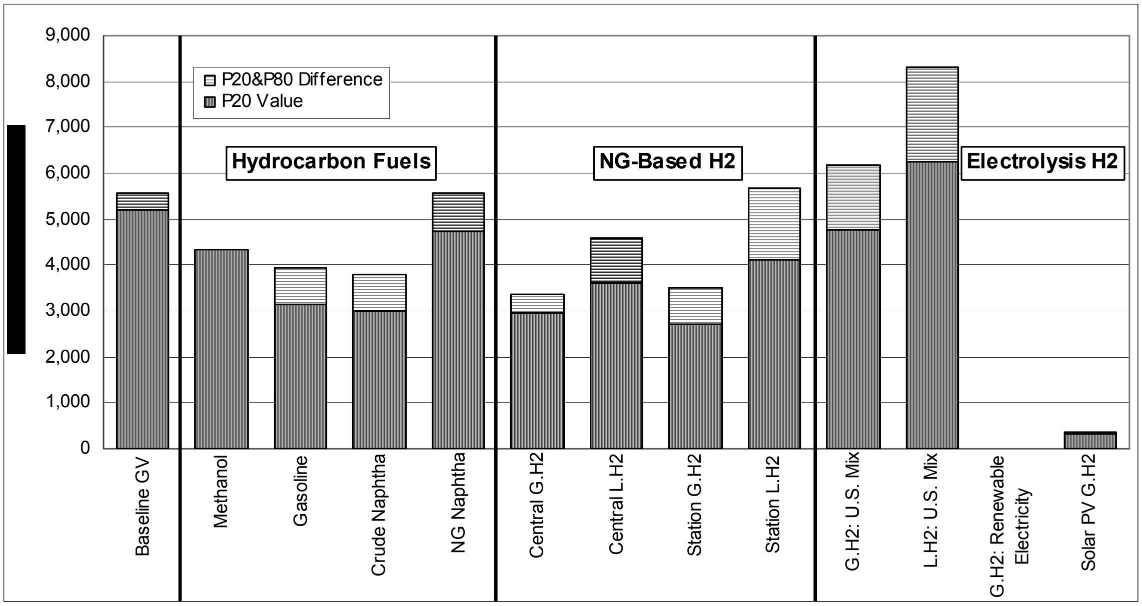


Figure 4. Per-Mile Well-to-Wheel Fossil Energy Use of Baseline GVs and FCVs

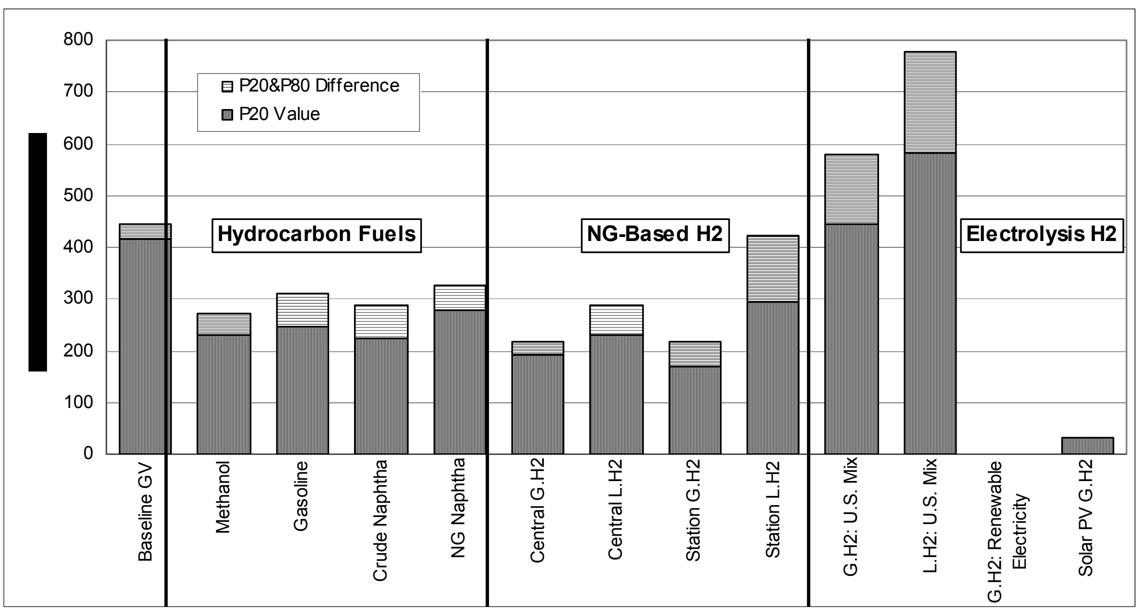


Figure 5. Per-Mile Well-to-Wheel Greenhouse Gas Emissions of Baseline GVs and FCVs

## 5. ACKNOWLEDGMENTS

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