General Motors Corporation

Argonne National Laboratory

BP

ExxonMobil

and

Shell

VOLUME I

Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems

– North American Analysis –

EXECUTIVE
SUMMARY
REPORT

June 2001

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DISCLAIMER

Because many factors critical to the potential commercial viability of the technologies addressed in this study lie beyond the scope of the study's analysis, this report cannot provide the basis for dependable predictions regarding marketplace feasibility or timetables for implementation or commercialization of the technologies examined herein.

Preface

Project Description and Acknowledgments

Need for the Study

There are differing yet strongly held views among the various “stakeholders” in the advanced fuel/propulsion system debate. In order for the introduction of advanced technology vehicles and their associated fuels to be successful, it seems clear that four important stakeholders must view their introduction as a “win”:

- Society,
- Automobile manufacturers and their key suppliers,
- Fuel providers and their key suppliers, and
- Auto and energy company customers.

If all four of these stakeholders, from their own perspectives, are not positive regarding the need for and value of these advanced fuels/vehicles, the vehicle introductions will fail.

This study was conducted to help inform public and private decision makers regarding the impact of the introduction of such advanced fuel/propulsion system pathways from a societal point of view. The study estimates two key performance criteria of advanced fuel/propulsion systems on a total system basis, that is, “well” (production source of energy) to “wheel” (vehicle). These criteria are energy use and greenhouse gas emissions per unit of distance traveled.

The study focuses on the U.S. light-duty vehicle market in 2005 and beyond, when it is expected that advanced fuels and propulsion systems could begin to be incorporated in a significant percentage of new vehicles. Given the current consumer demand for light trucks, the benchmark vehicle considered in this study is the Chevrolet Silverado full-size pickup.

How This Study Differs from Other Well-to-Wheel Analyses

This study differs from prior well-to-wheel analyses in a number of important ways:

1. The study considers fuels and vehicles that might, albeit with technology breakthroughs, be commercialized in large volumes and at reasonable prices. In general, fuels and propulsion systems that appear to be commercially viable only in niche markets are not considered.

2. The study provides best estimates and associated confidence bounds of the criteria mentioned above to allow the reader to assess differences between fuel/vehicle propulsion systems on a more statistically sound basis. This approach provides not only the best estimate, but also a measure of the uncertainty around the best estimate.

3. The study incorporates the results of a proprietary vehicle model created and used by General Motors.

4. The well-to-wheel analysis involved participation by the three largest privately owned fuel providers: BP, ExxonMobil, and Shell.

5. The 15 vehicles considered in the study include conventional and hybrid electric vehicles with both spark-ignition and compression-ignition engines, as well as hybridized and non-hybridized fuel cell vehicles with and without onboard fuel processors. All 15 vehicles were configured to meet the same performance requirements.

6. The 13 fuels considered in detail (selected from 75 different fuel pathways) include low-sulfur gasoline, low-sulfur diesel, crude oil-based naphtha, Fischer-Tropsch naphtha, liquid/compressed gaseous hydrogen based on five different pathways, compressed natural gas, methanol, and neat and blended (E85) ethanol. These 13 fuels, taken together with the 15 vehicles mentioned above, yielded the 27 fuel pathways analyzed in this study.

Format

The study was conducted and is presented in three parts:

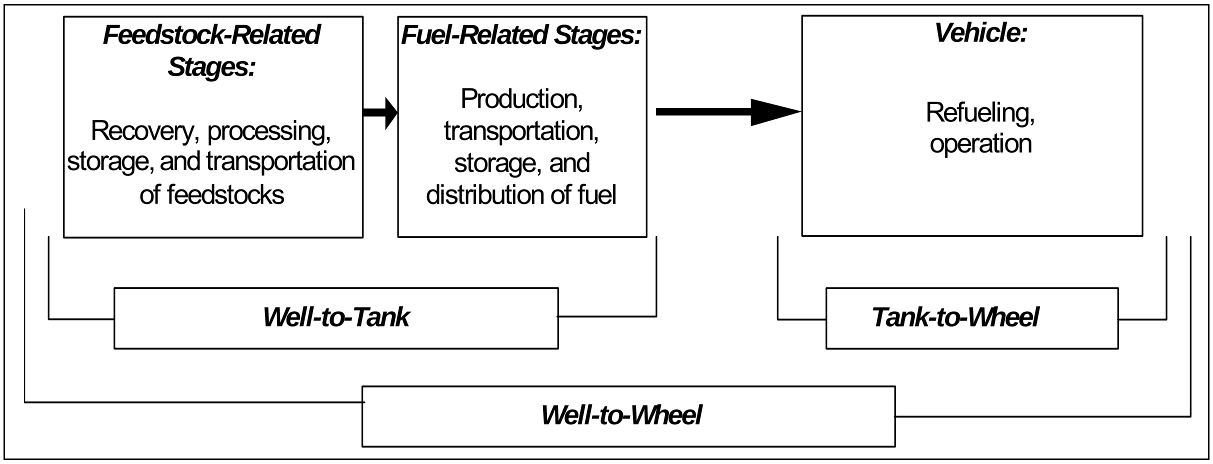
- Well-to-Tank (WTT): consideration of the fuel from resource recovery to delivery to the vehicle tank,

- Tank-to-Wheel (TTW): consideration of the vehicle from the tank to the wheel, and

- Well-to-Wheel (WTW): integration of the WTT and TTW components.

The following figure illustrates the stages involved in a full fuel-cycle analysis. Argonne's study covers the WTT (or feedstock and fuel-related) stages (Part 1). GM evaluated the fuel economy and emissions of various vehicle technologies using different fuels (TTW analysis) (Part 2). In a separate effort, Argonne's WTT results were combined with GM's TTW results to produce WTW results (Part 3).

Volume 1 of this report series contains the Executive Summary Report, Volume 2 the full three-part study report, and Volume 3 the complete WTT report submitted to GM by Argonne National Laboratory (including detailed assumptions and data).



Full Fuel-Cycle Analysis

Study Organization

Mr. Greg Ruselowski of General Motors' Global Alternative Propulsion Center (GAPC) initiated the study. The study team was organized as follows:

Program Management

Program Manager: Dr. James P. Wallace III, Wallace & Associates
Assistant Program Manager: Raj Choudhury, GM GAPC

Part 1: Well-to-Tank Analysis

Project Leader and Principal Researcher: Dr. Michael Wang, Argonne National Laboratory
Project Team: Dr. Dongquan He, Argonne National Laboratory
GM Project Manager: Dr. Anthony Finizza, AJF Consulting
Project Reviewers:
BP: Andrew Armstrong and Dr. James Simnick
ExxonMobil: Gilbert Jersey and Dr. John Robbins
Shell: Jean Cadu
GM: Norman Brinkman
Argonne National Laboratory: Dr. Dan Santini

Part 2: Tank-to-Wheel Analysis

Project Leader and Principal Researcher: Trudy Weber, GM R&D and Planning Center
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Project Reviewers:
GM R&D and Planning Center: Dr. Hazem Ezzat, Dr. Roger Krieger, and Norman Brinkman

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GM Powertrain: Dr. Fritz Indra, Tim Peterson, Arjun Tuteja, Dr. Ko-Jen Wu, and Tony Zarger
GM Truck: Dr. Tanvir Ahmad
GM ATV: Dr. Peter Savagian and John Hepke

Part 3A: Well-to-Tank Pathways Down Select

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Shell: Jean Cadu
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Part 3B: Well-to-Wheel Integration

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ExxonMobil: Gilbert Jersey and Dr. John Robbins
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GM: Norman Brinkman and Raj Choudhury
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Acknowledgments

In addition to the participants cited above, the Program Team wishes to acknowledge the support of the following people: Tom Bond, Manager of Global Fuels Technology, BP; Tim Ford, Vice President Fuels, Shell International Petroleum Co. Ltd.; Dr. Eldon Priestley, Manager, Corporate Strategic Research, ExxonMobil Research and Engineering; Dr. James Katzer, Strategic Planning and Programs Manager, ExxonMobil Research and Engineering; Dr. Byron McCormick, Director of GM GAPC; Dr. James A. Spearot, Director, Chemical and Environmental Sciences Lab, GM R&D and Planning Center; Dr. Larry Johnson, Director of Argonne National Laboratory's Transportation Technology R&D Center; and Robert Larsen, Director of Argonne National Laboratory's Center for Transportation Research, all of whom provided invaluable support in the ongoing review process for this report.

The study participants would like to thank Tien Nguyen, Dr. Phillip Patterson, and David Rodgers of the U.S. Department of Energy's Office of Transportation Technologies; without their support of previous versions of the GREET model, this study would not have been possible. We would also like to acknowledge the editorial support of Mary Fitzpatrick of Argonne.

Additional acknowledgments are made in each part of the full report.

Responsibility

Argonne assumes responsibility for the accuracy of Part 1 but acknowledges that this accuracy was enhanced through significant contributions and thorough review by the study team, especially participants from the energy companies cited.

GM is exclusively responsible for the quantification of comparative vehicle technologies considered in Part 2.

Part 3A sought to further down-select the 75 fuel pathways examined in Part 1 into fuels that appear to be potentially feasible at high volumes and reasonable prices. The three energy companies provided key input for the conclusions reached in this section.

The GM Well-to-Wheel Integration Model used for Part 3B was developed and simulated by AJF Consultants and Wallace & Associates and is the property of GM. GM, Argonne, and the energy companies have reviewed the model and its simulation results and find them consistent and rational, given the model input.

Next Steps

A follow-up study to estimate criteria pollutants for the United States is in the planning stage. In addition, efforts are underway to provide a European counterpart to this study.

Contents

Figures

Figures (Cont.)

Tables

Notation

Acronyms and Abbreviations

ANL	Argonne National Laboratory
CARFG2	California Phase 2 reformulated gasoline
CARFG3	California Phase 3 reformulated gasoline
CC	combined-cycle
CG	conventional gasoline
CH_4	methane
CIDI	compression ignition direct injection
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CONV	conventional vehicle
CS	charge sustaining
E100	neat (100%) ethanol
E85	a mixture of 85% ethanol and 15% gasoline (by volume)
EL	electrolysis
EPA	U.S. Environmental Protection Agency
EtOH	ethanol
FC	fuel cell
FCV	fuel cell vehicle
FG	flared gas
FP	fuel processor
FRFG2	Federal Phase 2 reformulated gasoline
FT	Fischer-Tropsch
FTD	Fischer-Tropsch diesel
$G.H_2$	gaseous hydrogen
GAPC	Global Alternative Propulsion Center (General Motors Corporation)
GASO	gasoline
GHG	greenhouse gas
GM	General Motors Corporation
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP	global warming potential
H_2	hydrogen
HE100	herbaceous E100
HE85	herbaceous E85
HEV	hybrid electric vehicle
HPSP	Hybrid Powertrain Simulation Program
$L.H_2$	liquid hydrogen
MeOH	methanol
MTBE	methyl tertiary butyl ether
N_2O	nitrous oxide
NA	North American

NAP	naphtha
NG	natural gas
NiMH	nickel metal hydride
NNA	non-North-American
NO_x	nitrogen oxide
PM_{10}	particulate matter with diameter of 10 μm or less
PNGV	Partnership for a New Generation of Vehicles
SI	spark ignition
SO_x	sulfur oxides
SULEV	Super Ultra-Low Emissions Vehicle
TTW	tank-to-wheel
USDA	U.S. Department of Agriculture
VOC	volatile organic compound
WTT	well-to-tank
WTW	well-to-wheel
ZEV	Zero Emissions Vehicle

Units of Measure

Btu	British thermal unit(s)
g	gram(s)
gal	gallon(s)
kWh	kilowatt hour(s)
mi	mile(s)
mmBtu	million (10^6) Btu
mph	mile(s) per hour
ppm	part(s) per million
µm	micrometer(s)

PART 1

Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels

ES-1.1 Introduction

The various fuels proposed for use in fuel cell vehicles (FCVs) and hybrid electric vehicles (HEVs) are subject to different production pathways and, consequently, result in different energy and greenhouse gas (GHG) emission impacts. The purpose of this study, conducted by Argonne National Laboratory's Center for Transportation Research and commissioned by the Global Alternative Propulsion Center (GAPC) of General Motors Corporation (GM), was to evaluate the energy and GHG emission impacts associated with producing different transportation fuels. For the study, Argonne examined energy use and GHG emissions from well to fuel available in the vehicle tank (well-to-tank [WTT] analysis). Three energy companies — BP, ExxonMobil, and Shell — participated in the study by providing input and reviewing Argonne's results. The timeframe for the WTT analysis is 2005 and beyond.

ES-1.2 Methodology

To complete Part 1 of the study, a model developed by Argonne was used to estimate WTT energy and emission impacts of alternative transportation fuels and advanced vehicle technologies. The model, called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), calculates energy use in British thermal units per mile (Btu/mi) and emissions in grams per mile (g/mi) for transportation fuels and vehicle technologies.

For energy use modeling, GREET computes total energy use (all energy sources), fossil energy use (petroleum, natural gas, and coal), and petroleum use. For emissions modeling, GREET estimates three major GHGs specified in the Kyoto protocol (carbon dioxide [CO_2]), methane [CH_4], and nitrous oxide [N_2O]) and five criteria pollutants (volatile organic compounds [VOCs], carbon monoxide [CO], nitrogen oxides [NO_x] particulate matter with diameters of 10 μm or less [PM_{10}], and sulfur oxides [SO_x]). The three GHGs are combined with their global warming potentials (GWPs) to calculate CO_2-equivalent GHG emissions. With the assistance of the project team, Argonne modified the GREET model to make it stochastic in nature, i.e., providing confidence bounds around best estimates to quantify uncertainty.

For this study, we estimated total energy, fossil energy, and petroleum use, as well as CO_2-equivalent emissions of the three GHGs. Emissions of criteria pollutants were not included in this study.

Fuels and Production Pathways

We analyzed 75 fuel pathways for application to HEVs and FCVs. The following sections briefly describe the fuels and production pathways chosen for our study. Volume 2 of this report series provides a complete list of the 75 production pathways analyzed and results for the 30 selected pathways. Volume 3 of this report series provides analysis results for all 75 pathways and details regarding the assumptions used in our study. Appendices A and B in Volume 3 provide charts showing the probability distribution functions for key input parameters and results for all 75 pathways.

Petroleum-Based Fuels

The TTW study included three petroleum-based fuels: gasoline, diesel, and naphtha. For gasoline and diesel, we established cases to represent different fuel requirements. For gasoline, we considered federal conventional gasoline (CG), federal Complex Model Phase 2 reformulated gasoline (FRFG2), California Phase 2 reformulated gasoline (CARFG2), California Phase 3 reformulated gasoline (CARFG3), and the gasoline requirements in the U.S. Environmental Protection Agency's (EPA's) Tier 2 vehicle emission standards. These gasoline options contain sulfur at concentrations ranging from 5 parts per million (ppm) to over 300 ppm and may contain methyl tertiary butyl ether (MTBE), ethanol (EtOH), or no oxygenate.

For on-road diesel fuels, we included two options: a current diesel and a future diesel. The current diesel has a sulfur content of 120–350 ppm. The future diesel, which reflects the new diesel requirement adopted recently by EPA, has a sulfur content below 15 ppm.

Naphtha could serve as a fuel cell fuel. Virgin crude naphtha from petroleum refineries' distillation (without desulfurization) has a sulfur content of about 370 ppm. For fuel cell applications, we assumed that the sulfur content of crude naphtha would be reduced to about 1 ppm.

Natural-Gas-Based Fuels

We included these natural gas (NG)-based fuels: compressed natural gas (CNG), methanol (MeOH), Fischer-Tropsch diesel (FTD), Fischer-Tropsch naphtha, gaseous hydrogen ($G.H_2$) produced in central plants, $G.H_2$ produced in refueling stations, liquid hydrogen ($L.H_2$) produced in central plants, and $L.H_2$ produced in refueling stations. These fuels are produced from three NG feedstock sources: North American (NA) sources, non-North-American (NNA) sources, and NNA flared gas (FG) sources.

Bio-Ethanol Options

We included three ethanol production pathways: ethanol from corn, woody biomass (trees), and herbaceous biomass (grasses). Corn-based ethanol can be produced in wet milling or dry milling plants; we examined both. Corn-based ethanol plants also produce other products (primarily animal feeds). We allocated energy use and emissions between ethanol and its co-products by using the market value method.

In cellulosic (woody and herbaceous) ethanol plants, while cellulose in biomass is converted into ethanol through enzymatic processes, the lignin portion of biomass can be burned to provide needed steam. Co-generation systems can be employed to generate both steam and electricity. In this case, extra electricity can be generated for export to the electric grid. We took the generated electricity credit into account in calculating energy use and GHG emissions of cellulosic ethanol production.

Electricity Generation

Electricity plays a major role in battery-powered electric vehicles (EVs), grid-connected (or charge-depleting) HEVs, and hydrogen (H_2) production via electrolysis. One of the key factors in determining the energy use and GHG emissions associated with electricity generation is electric generation mix (the mix of the power plants fired with different fuels). We included three generation mixes in our study — the U.S., California, and Northeast U.S — to cover a broad range. NG-fired combined-cycle (CC) turbines with high energy-conversion efficiencies have been added to U.S. electric generation capacity in the last decade. We estimated energy use and GHG emissions associated with electricity generation in NG CC power plants, hydroelectric plants, and nuclear power plants separately.

Emissions estimates were calculated for four types of electric power plants: oil-fired, NG-fired, coal-fired, and nuclear. Other power plants, such as hydroelectric and windmill plants, generate virtually no operational emissions. Emissions from nuclear power plants are attributable to uranium recovery, enrichment, and transportation. Our estimate of emissions associated with electricity generation includes fuel production stages as well as electricity generation.

Hydrogen Production via Electrolysis

Production of H_2 from electricity (by electrolysis of water at refueling stations) may represent a means to provide H_2 for fuel cell vehicles. We evaluated H_2 production from electricity generated from hydroelectric and nuclear power, as well as from the three generation mixes (U.S., California, Northeast U.S) and NG-fired CC turbines. The first two cases represent electricity generation with zero or near-zero GHG emissions.

Probability Distribution Functions for Key Parameters

On the basis of our research of the efficiencies of WTT stages and input from the energy companies during this study, we determined probability distribution functions for key WTT stages (for details, see Appendix A in Volume 3 of this report series). The probabilistic simulations employed in this study, a departure from the range-based simulations used in many previous Argonne studies, are intended to address uncertainties statistically. For each activity associated with the production process of each fuel, we determined the following parametric values for probability: 20%, 50%, and 80% (P20, P50, and P80). For most parameters, we assumed normal probability distributions. For some of the parameters, where a normal distribution would not describe the parameter correctly, we assumed a triangular distribution.

Transportation of Feedstocks and Fuels

We employed the following five-step approach to estimate energy use and GHG emissions for transportation of feedstocks and fuels.

- Determine transportation modes and their shares (i.e., ocean tankers, pipelines, barges, rail, and trucks) to be used to transport a given feedstock or fuel.

- Identify the types and shares of process fuels (e.g., residual oil, diesel fuels, natural gas, electricity) to be used to power each mode.

- Calculate the energy intensity and emissions associated with each transportation mode fueled with each process fuel.
- Estimate the distance of each transportation mode for each feedstock or fuel.
- Add together the energy use and emissions of all transportation modes for transporting the given feedstock or fuel.

ES-1.3 Results

In our analysis, we found that many pathways to produce a given fuel were similar, so we were able to select a representative pathway. Other pathways were eliminated for reasons detailed in Volume 3 of this report series. In the end, we selected the 30 pathways listed in Table ES-1.1. In selecting the 30 pathways for presentation here, we did not include fuel plant designs with steam or electricity co-generation. These design options provide additional energy and emissions benefits for the fuels evaluated here (namely, $G.H_2$, methanol, FT naphtha, and FTD), but whether these options are considered appropriate depends on the specific plant location relative to an energy infrastructure and potential customers. Moreover, in reality, these options could be considered for any fuel-producing facility. We also eliminated all pathways based on flared gas. FG-based pathways offer significant energy and emissions benefits; however, the amount of FG represents a small portion of the resource base. Results of all eliminated pathways are presented in Appendix B to Volume 3 of this report series. The following paragraphs discuss the results in terms of total energy use, fossil energy use, petroleum use, and GHG emissions.

Table ES-1.1 Representative Fuel Pathways Identified

Fuel Pathways
Petroleum-Based
(1) Conventional (current) gasoline
(2) 5–30 ppm sulfur (low-sulfur) RFG without oxygenate (future gasoline)
(3) Conventional (current) diesel
(4) Low-sulfur (LS) (future) diesel
(5) Crude naphtha
NG-Based
(6) CNG: NA NG
(7) CNG: NNA NG
(8) MeOH: NA NG [a]
(9) MeOH: NNA NG [a]
(10) FT naphtha: NA NG [a]
(11) FT naphtha: NNA NG [a]
(12) FTD: NA NG [a]
(13) FTD: NNA NG [a]
(14) $G.H_2$ – central plants: NA NG [a]
(15) $G.H_2$ – central plants: NNA NG [a]
(16) $L.H_2$ – central plants: NA NG [a]
(17) $L.H_2$ – central plants: NNA NG [a]
(18) $G.H_2$ – stations: NA NG [a]
(19) $G.H_2$ – stations: NNA NG [a]
(20) $L.H_2$ – stations: NA NG [a]
(21) $L.H_2$ – stations: NNA NG [a]
Electricity-Based
(22) Electricity: U.S. mix
(23) Electricity: CC turbines, NA NG-fired
Electrolysis-Based [b]
(24) $G.H_2$ electrolysis: U.S. mix
(25) $G.H_2$ electrolysis: CC turbine, NA NG
(26) $L.H_2$ electrolysis: U.S. mix
(27) $L.H_2$ electrolysis: CC turbine, NA NG
Ethanol-Based
(28) E100: corn (wet mill, market value) [c]
(29) E100: herbaceous cellulose [c]
(30) E100: woody cellulose [c]

[a] Without steam or electricity co-generation.

[b] In the case of electrolysis, water is converted to hydrogen and oxygen through the use of electricity, so both water and electricity are treated as feedstocks.

[c] Ethanol contains 5% gasoline as a denaturant.

Total Energy Use

Total energy use from fuel production, i.e., WTT energy loss, is presented in Figure ES-1.1.[1] We found that petroleum-based fuels offer the lowest total energy use for each unit of energy delivered to vehicle tanks (see Figure ES-1.1, in which the tops and bottoms of the bars indicate the 80 and 20 percentiles, respectively). NG-based fuels (except CNG) generally use a large amount of total energy. The fuels with the highest energy use are L.H_2 (production in both central plants and refueling stations), G.H_2 and L.H_2 production via electrolysis, electricity generation, and cellulosic ethanol. L.H_2 suffers large efficiency losses during H_2 liquefaction. H_2 production via electrolysis suffers two large efficiency losses: electricity generation and H_2 production.

Total energy use by electricity generation is reduced when using NG-fired CC turbines rather than the U.S. electric generation mix because the average conversion efficiency of existing U.S. fossil fuel plants is 32–35%; the conversion efficiency of NG-fired CC turbines is over 50%.

Use of NNA NG for NG-based fuel production results in slightly higher total energy use than does use of NA NG, because transportation of liquid fuels to the United States consumes additional energy. In the cases of CNG, G.H_2, and station-produced L.H_2, the requirement for NG liquefaction for shipment of NNA gas sources to North America causes additional energy efficiency losses.

Fossil Energy Use

Fossil fuels include petroleum, NG, and coal — the three major nonrenewable energy sources. Except for ethanol pathways, the patterns of fossil energy use are similar to those of total energy use (see Figure ES-1.2). For woody and herbaceous (cellulosic) ethanol pathways, the difference is attributable to the large amount of lignin burned in these ethanol plants. We accounted for the energy in lignin in calculating total energy use, but not in calculating fossil energy use. So fossil energy use is much lower than total energy use for the two cellulosic ethanol pathways.

For electricity generation and H_2 production via electrolysis, fossil energy use between the U.S. generation mix and NG-fired CC turbines is very similar because, while the U.S. generation mix has an overall conversion efficiency lower than that of CC turbines, some non-fossil fuel power plants under the U.S. average mix (such as nuclear and hydroelectric power plants) do not contribute to fossil energy use.

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[1] Normally, results presented in the electrolysis and electricity pathways in GREET simulations include both energy losses from WTT and energy contained in the fuel delivered. Figures ES-1.1 and ES-1.2 present energy losses only.

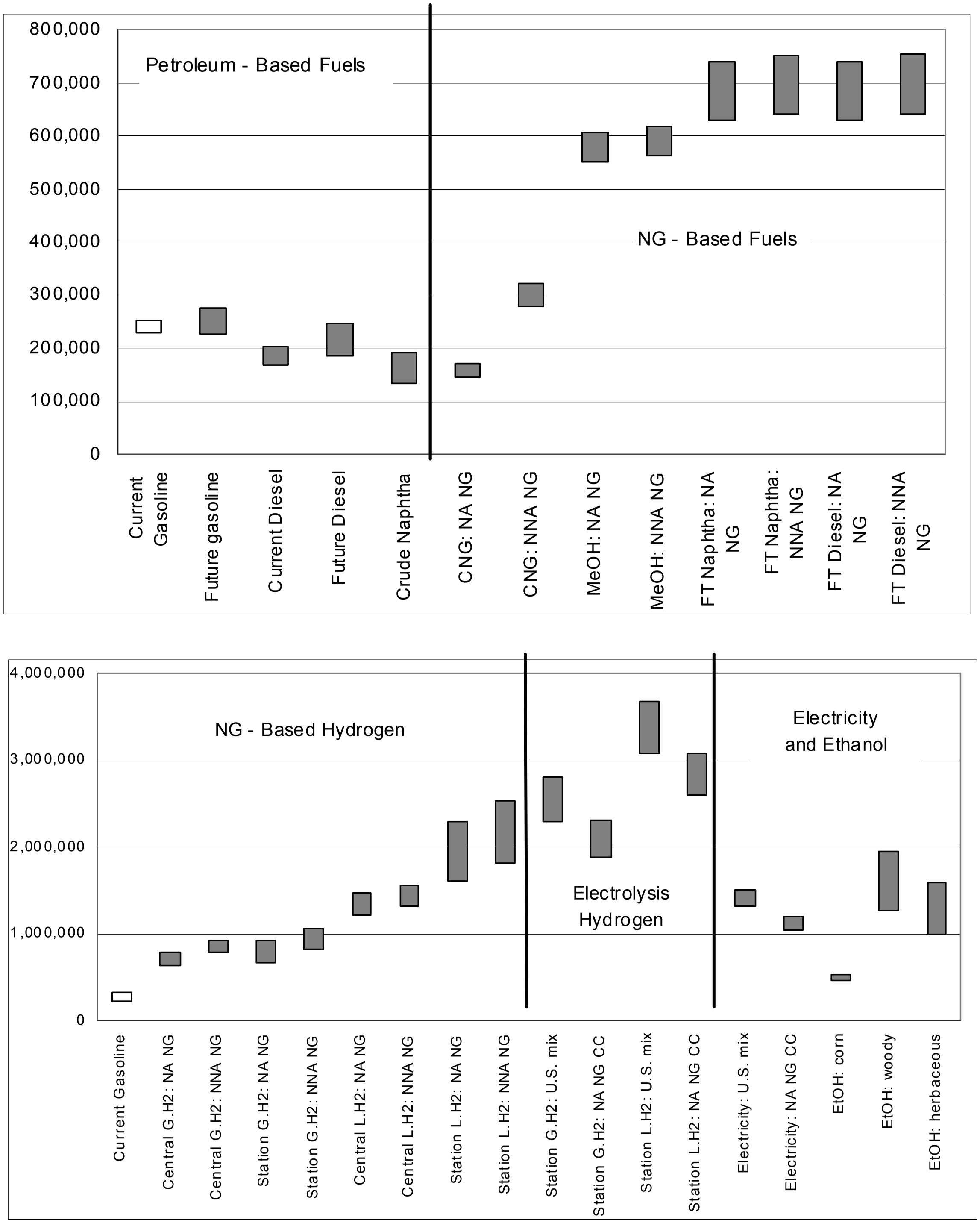

Figure ES-1.1 WTT Total Energy Use (Btu/mmBtu of fuel delivered to vehicle tanks)

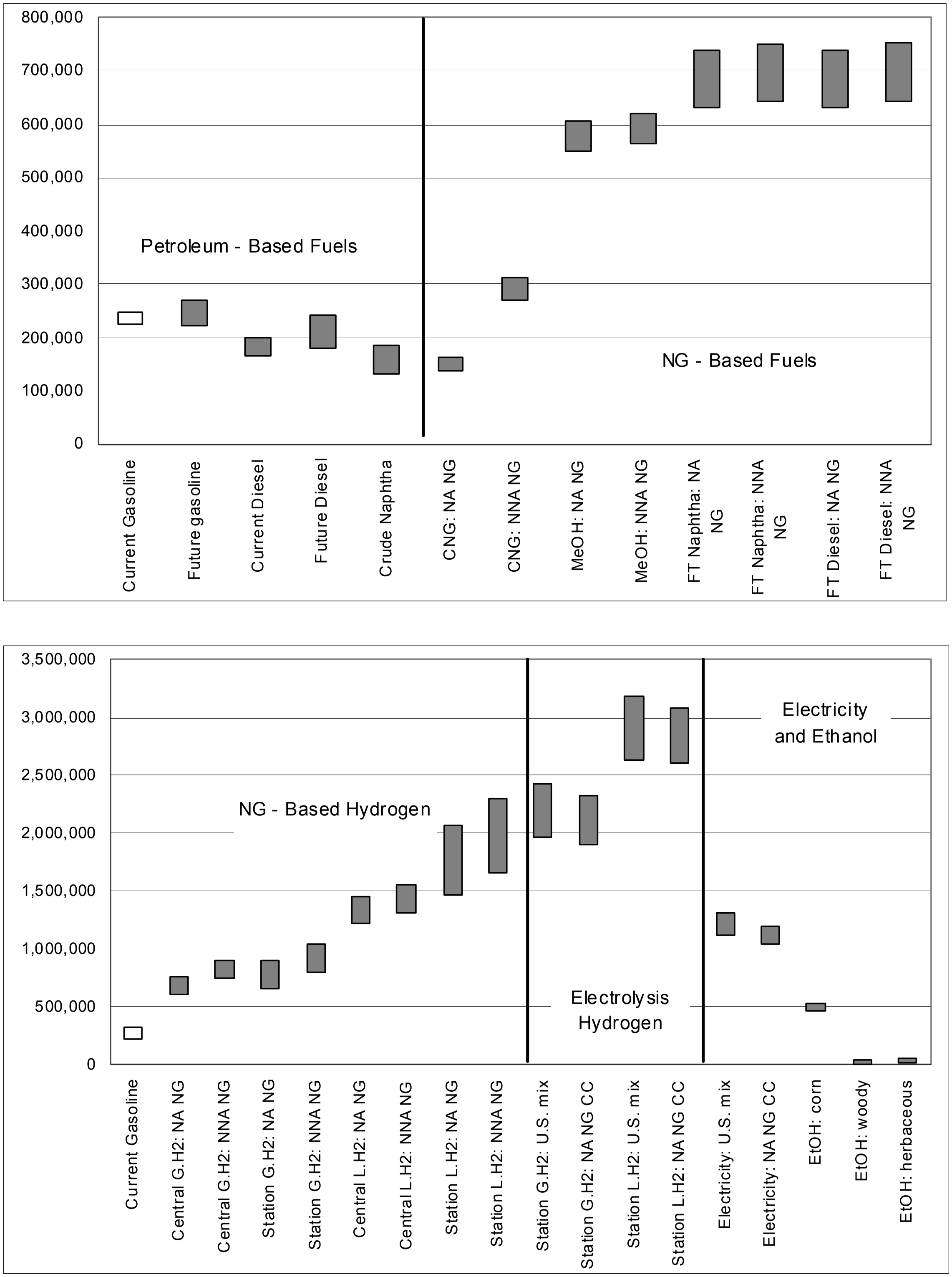

Figure ES-1.2 WTT Fossil Energy Use (Btu/mmBtu of fuel delivered to vehicle tanks)

Petroleum Use

As expected, production of all petroleum-based fuels involves high petroleum use (see Figure ES-1.3). Methanol pathways have relatively high petroleum use because trucks and rails are used to transport a large quantity of methanol.

For electricity generation and H_2 production via electrolysis, we observed a large reduction in petroleum use from the U.S. average generation mix to NG-fired CC turbines because, under the U.S. generation mix, some (a small amount) electricity is generated by burning residual oil. In addition, mining and transportation of coal consume a significant amount of oil.

The high petroleum use for centrally produced G.H_2, relative to station-produced G.H_2, is attributable to the fact that the former is compressed in refueling stations with electric compressors only, while the latter is compressed by means of both electric and NG compressors. Electricity pathways also consume some petroleum.

The amount of petroleum used in the three ethanol pathways is similar to that used in the gasoline pathways because a large amount of diesel fuel is consumed during farming and during transportation of corn and cellulosic biomass.

Greenhouse Gas Emissions

Figure ES-1.4 shows the sum of WTT CO_2-equivalent emissions of CO_2, CH_4, and N_2O. Petroleum-based fuels and CNG produced from NA NG are associated with low WTT GHG emissions because of their high production efficiency. CNG from NNA NG has relatively high GHG emissions because of CH_4 emissions generated from liquid NG boiling-off and leakage during transportation (CH_4, a GHG, is 21 times as potent as CO_2). Methanol and FT fuels have high GHG emissions because of CO_2 emissions during fuel production that result from their low production efficiency relative to that of petroleum-based fuels.

All H_2 pathways have very high GHG emissions because all of the carbon in NG feedstock is removed during H_2 production, for which we did not assume carbon sequestration. For the electrolysis cases, CO_2 releases during electricity generation (attributable to fossil-fueled generation) are significant. L.H_2 production, electrolysis H_2 (both gaseous and liquid), and electricity generation have the highest GHG emissions. Relative to emissions from NG-fired CC turbine plants, there is a large increase in GHG emissions from the U.S. average electric generation mix, primarily because of the high GHG emissions from coal- and oil-fired electric power plants. Coal- and oil-fired plants contribute a large share of the U.S. average.

The three ethanol pathways have negative GHG emissions because of carbon uptake sequestration during growth of corn plants, trees, and grass. Corn ethanol has smaller negative GHG values because use of fossil fuels during corn farming and in ethanol plants offsets some of the CO_2 sequestered during growth of corn plants. All the carbon sequestered during biomass growth is released back to the air during combustion of ethanol in vehicles, which is accounted for in the integration of the well-to-tank and tank-to-wheel analyses in Part 3.

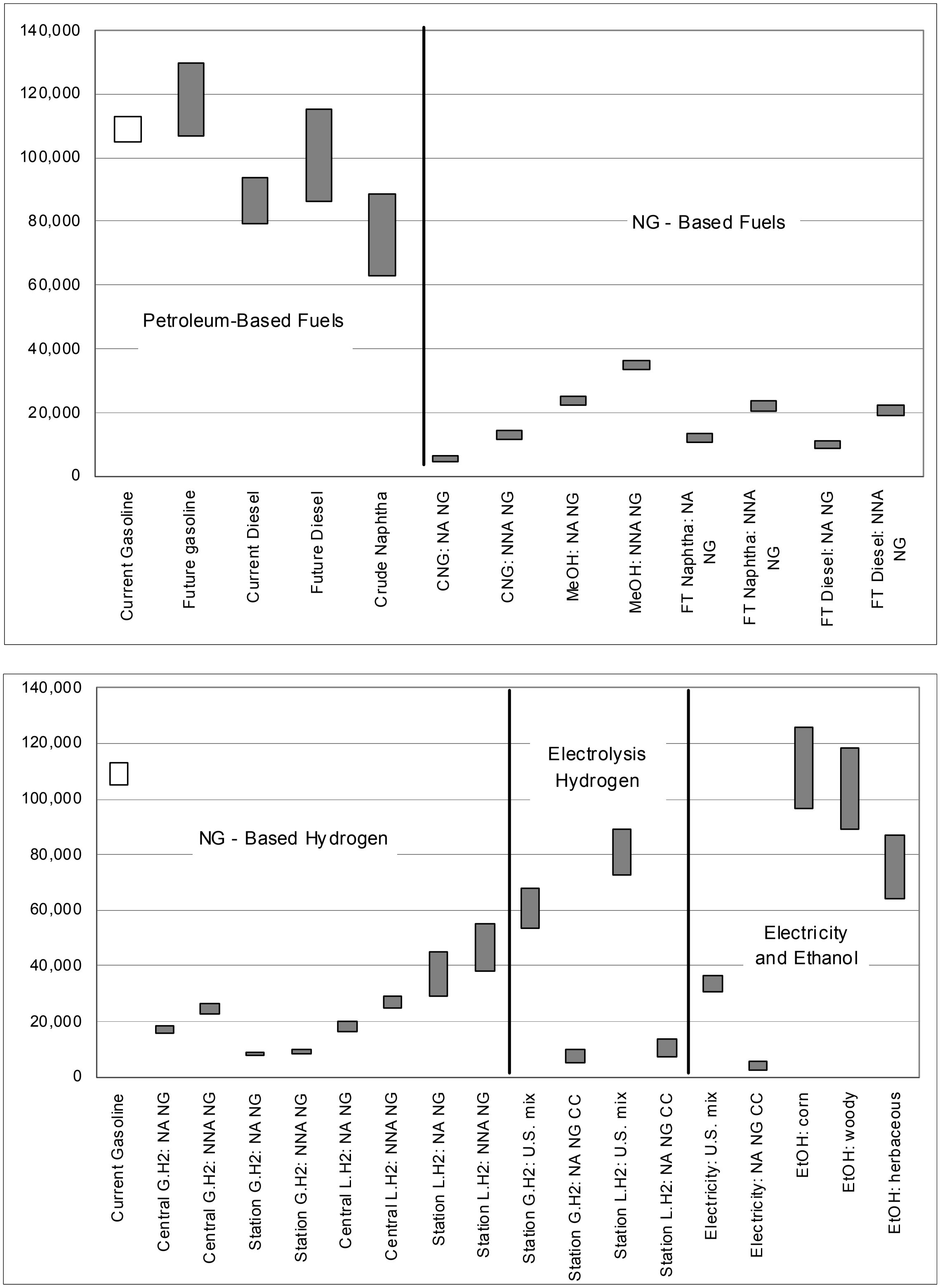

Figure ES-1.3 WTT Petroleum Use (Btu/mmBtu of fuel delivered to vehicle tanks)

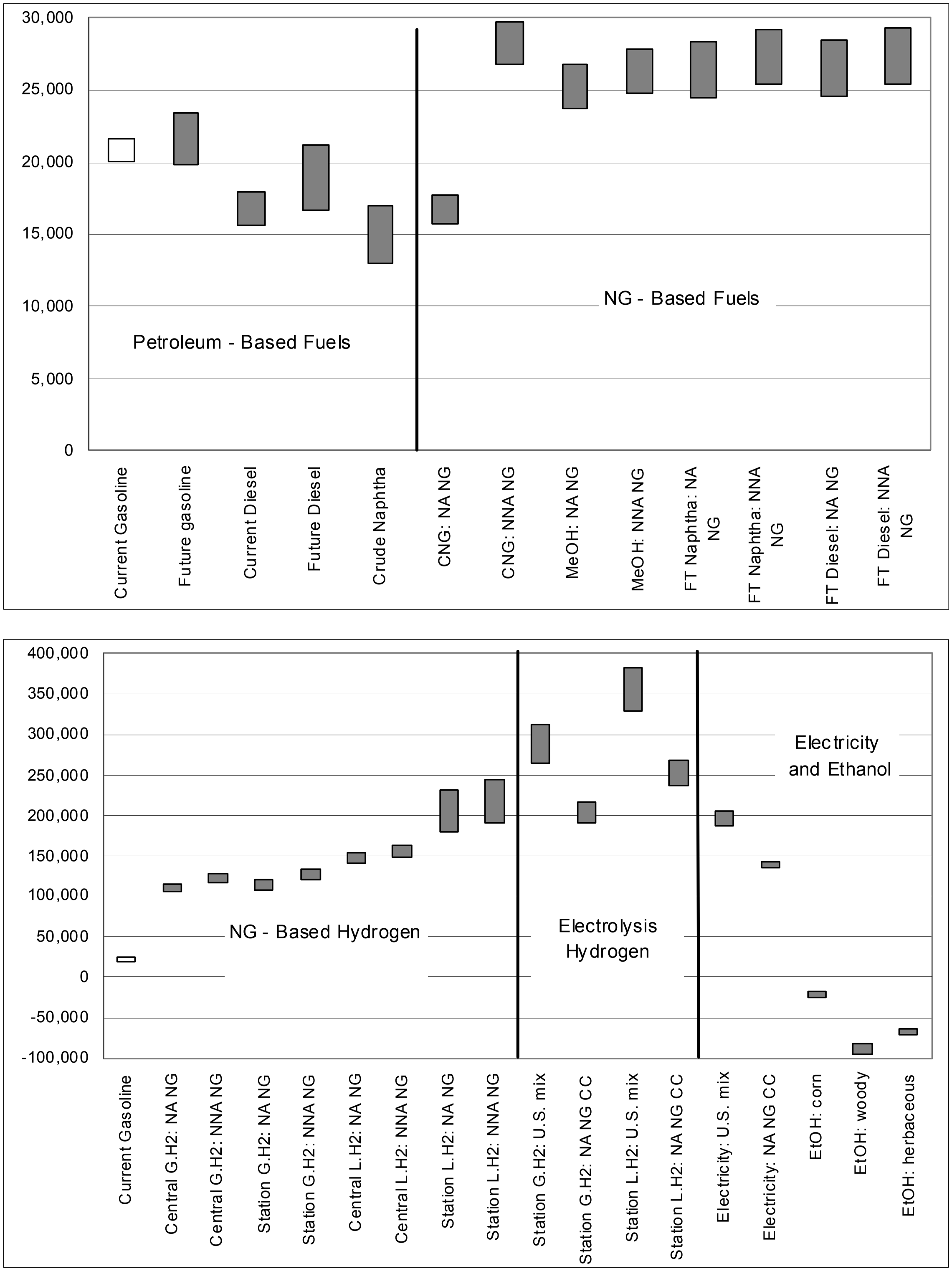

Figure ES-1.4 WTT GHG Emissions (g/mmBtu of fuel delivered to vehicle tanks)

ES-1.4 Conclusions

Our WTT analysis resulted in the following conclusions. It is important to remember that WTT results are incomplete in evaluating fuel/propulsion systems. The systems must be evaluated on a WTW basis; this analysis is presented in Part 3 of this volume.

- *Total Energy Use.* For the same amount of energy delivered to the vehicle tank for each of the fuels evaluated in our study, petroleum-based fuels and CNG are subject to the lowest WTT energy losses. Methanol, FT naphtha, FTD, G.H_2 from NG, and corn-based ethanol are subject to moderate WTT energy losses. Liquid H_2 from NG, electrolysis H_2 (gaseous and liquid), electricity generation, and cellulosic ethanol are subject to large WTT energy losses.

- *Fossil Energy Use.* Fossil energy use — including petroleum, NG, and coal — follows patterns similar to those for total energy use, except for cellulosic ethanol. Although WTT total energy use of cellulosic ethanol production is high, its fossil energy use is low because cellulosic ethanol plants would burn lignin, a non-fossil energy, for needed heat.

- *Petroleum Use.* Production of all petroleum-based fuels requires a large amount of petroleum. Electrolysis H_2 (with the U.S. average electricity) and the three ethanol pathways consume an amount of petroleum about equal to that consumed by petroleum-based fuels. NG-based fuel pathways require small amounts of petroleum.

- *Greenhouse Gas Emissions.* Production of petroleum-based fuels and NG-based methanol, FT naphtha, and FTD results in a smaller amount of WTT GHG emissions than production of H_2 (gaseous and liquid) and electricity generation. WTT GHG emission values of the three ethanol pathways are negative because of carbon sequestration during growth of corn plants, trees, and grass.

Overall, our WTT analysis reveals that petroleum-based fuels have lower WTT total energy use than do non-petroleum-based fuels. L.H_2 production (in both central plants and refueling stations) and production of G.H_2 and L.H_2 via electrolysis can be energy-inefficient and can generate a large amount of WTT GHG emissions. Cellulosic ethanol, on the other hand, because it is produced from renewable sources, offers significant reductions in GHG emissions. The other fuel options examined here have moderate WTT energy and GHG emissions effects.

PART 2

Tank-to-Wheel Energy Use for a North American Vehicle

ES-2.1 Introduction

The purpose of this portion of the study, conducted by GM, was to quantify the tank-to-wheel (TTW) energy use of advanced conventional and unconventional powertrain systems, focusing on technologies that are expected to be implemented in 2005–2010. We assessed these technologies on the basis of their potential for improving fuel economy while maintaining the vehicle performance demanded by North American consumers.

It is very important to recognize that certain major factors — specifically, packaging, transient response, cold-start performance, and cost — were not taken into consideration in this study. Therefore, the results should not be considered indicative of commercial viability; they should be viewed rather as an initial screening to identify configurations that are sufficiently promising to warrant more detailed studies and should be compared to one another on a relative, rather than an absolute, basis.

ES-2.2 Methodology

We selected a full-size pickup truck as the baseline vehicle for this study. The GM proprietary Hybrid Powertrain Simulation Program (HPSP) vehicle simulation model was used to design and analyze each vehicle concept. With an extensive database of proprietary component maps, the HPSP can be used to model any conventional or advanced vehicle architecture or powertrain technology. We employed validated component characteristics to establish the fuel economy and energy required on the U.S. Environmental Protection Agency (EPA) urban and highway duty cycles.

Vehicle Architectures and Fuels

The following vehicle architectures and fuels were included in our study:

1. Conventional (CONV) vehicle with spark ignition (SI) gasoline engine (baseline)
2. CONV vehicle with compression ignition direct injection (CIDI) diesel engine
3. CONV vehicle with SI E85 (a mixture of 85% ethanol and 15% gasoline by volume) engine
4. CONV vehicle with SI compressed natural gas (CNG) engine
5. Charge-sustaining (CS) parallel hybrid electric vehicle (HEV) with gasoline engine
6. CS parallel HEV with CIDI diesel engine
7. CS parallel HEV with SI E85 engine
8. Gasoline fuel processor (FP) fuel cell vehicle (FCV)
9. Gasoline FP fuel cell (FC) HEV
10. Methanol FP FCV

11. Methanol FP FC HEV
12. Ethanol FP FCV
13. Ethanol FP FC HEV
14. Gaseous hydrogen ($G.H_2$)/liquid hydrogen ($L.H_2$) FCV
15. $G.H_2/L.H_2$ FC HEV

The baseline vehicle powertrain consisted of a gasoline engine and a 4-speed automatic transmission with a torque converter. The same transmission was used in the conventional architecture to run a diesel, an E85, and a CNG engine.

The parallel hybrid architecture selected for this study was an Input Power-Assist HEV with an electric drive at the transmission input, a 4-speed automatic transmission without a torque converter, and a full-size engine. We assumed that the electric drive could replace the torque converter and assist the engine for maximum vehicle acceleration performance. To maximize fuel economy, we implemented a charge-sustaining energy management strategy with fuel shutoff during standstill and deceleration and with battery launch at low acceleration demands. Gasoline, E85, and diesel engines were evaluated in this architecture.

We included fuel processor fuel cell systems in direct-drive and HEV powertrain architectures fueled by gasoline, methanol, and ethanol, as well as direct fuel cell and fuel cell HEV systems. The fuel processor and fuel cell HEV systems were also optimized with charge-sustaining energy management strategies.

Vehicle Simulation Model Input Data

The baseline vehicle design parameters used in the study — such as mass and aerodynamic and rolling resistance coefficients — were based on a GM full-size pickup truck. The mass was adjusted for each vehicle’s propulsion system independently; all other vehicle-level parameters were used consistently in all simulation models. We used the electric components based on validated maps for the electric drive system in the GM Precept (developed for the Partnership for a New Generation of Vehicles [PNGV]) and the nickel metal hydride (NiMH) battery technology.

Fuel cell stack and fuel processor component maps were based on small- to full-scale component data using GM proprietary modeling tools and validated on the GM HydroGen-1 FCV. The efficiency maps were based on a combination of current data and relatively near-term (one- to two-year timeline) projections. However, we recognize that significant development is required to scale up to the high power levels required for this application, specifically in the areas of thermal and water management, fuel processor dynamics, and startup.

Performance Targets

The performance targets shown in Figure ES-2.1 drove the powertrain sizing process. These metrics, evaluated through simulations, served as the design criteria for each vehicle concept. We determined vehicle mass on the basis of component sizes and optimized the powertrain operation on the driving cycles by implementing energy management and control strategies to achieve the

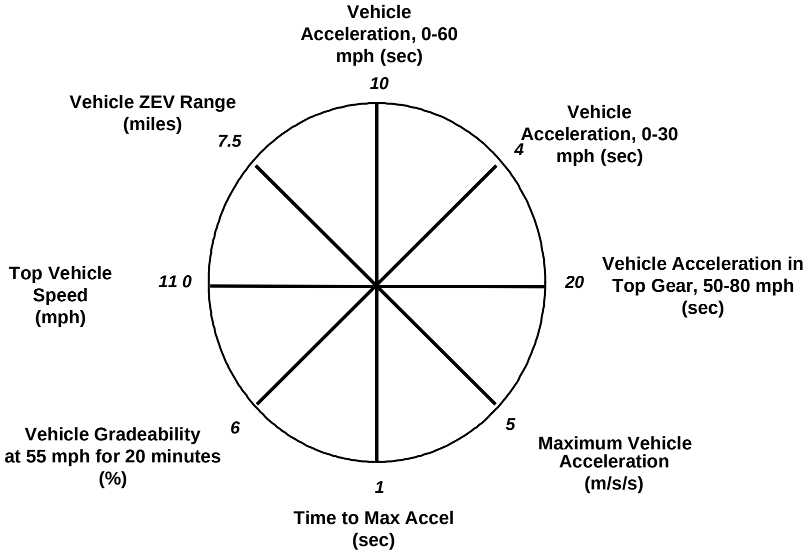

Figure ES-2.1 Performance Targets

maximum fuel economy for each vehicle concept. To provide more realistic and realizable fuel economy projections, we imposed constraints on component operation (e.g., engine, accessories, motors, batteries) to reflect vehicle driveability and comfort requirements. An additional requirement was that the vehicles suffer no performance degradation because of a lack of available energy from the battery (i.e., avoiding the so-called “turtle” effect). It should be noted that battery electric and charge-depleting battery electric HEVs were omitted from this detailed analysis because of their inability to meet overall vehicle range and other truck-related performance requirements.

Emissions Targets

Emissions targets for all vehicles were based on Federal Tier 2 standards, which are divided into eight emission level categories (or bins) for the 2010 timeframe, when the Tier 2 standards will be completely phased in. We selected Bin 5 standards for all vehicles with internal combustion engines because they represent the fleet average. Bin 5 standards are also consistent with PNGV goals. Bin 2 standards (equivalent to Super Ultra-Low Emissions Vehicle [SULEV] II) were selected for the fuel processor/reformer FCVs, and Bin 1 (Zero-Emissions Vehicle [ZEV]) standards were selected for the hydrogen FCVs. Compliance with these standards has not been demonstrated; we assumed that considerable advances will be made in the technologies. The impact of emissions control on fuel consumption was included in this analysis.

ES-2.3 Results

Table ES-2.1 presents the simulation results for each of the vehicle concepts included in this study. The only performance metric reported here is the 0–60 miles per hour (mph) performance time, which varies from vehicle to vehicle because the active constraints in each of these designs

Table ES-2.1 Fuel Economy and Performance Predictions

No.	Vehicle Configuration	Urban Fuel Economy (mpg GE)[a]	Highway Fuel Economy (mpg GE)	Complete Fuel Economy (mpg GE)	Gain in Fuel Economy over Baseline (%)	Tank to Wheels Efficiency (%)	Time (s to 60 mph)
1	Gasoline CONV SI	17.4	25.0	20.2	Baseline	16.7	7.9
2	Diesel CONV CIDI	20.2	30.4	23.8	18	19.4	9.2
3	E85 CONV SI	17.4	25.0	20.2	0	16.7	7.9
4	CNG CONV SI	17.0	24.7	19.8	-2	16.9	8.2
5	Gasoline SI HEV [b, c]	23.8	25.1	24.4	21	20.7	6.3
6	Diesel CIDI HEV [c]	29.1	29.8	29.4	46	24.6	7.2
7	E85 SI HEV [c]	23.8	25.1	24.4	21	20.7	6.3
8	Gasoline FP FCV	26.2	28.6	27.2	35	24.0	10.0
9	Gasoline FP FC HEV	31.9	28.5	30.2	50	27.3	9.9
10	Methanol FP FCV	28.8	32.4	30.3	50	26.6	9.4
11	Methanol FP FC HEV	35.8	33.0	34.5	71	31.1	9.8
12	Ethanol FP FCV	27.5	30.0	28.6	42	25.2	10.0
13	Ethanol FP FC HEV	33.5	29.9	31.8	57	28.7	9.9
14	G.H_2 FCV/ L.H_2 FCV	41.6	45.4	43.2	114	36.3	8.4
15	G.H_2 FC HEV/L.H_2 FC HEV	51.5	44.5	48.1	138	41.4	10.0

[a] GE = gasoline equivalent.
[b] All HEVs are charge sustaining.
[c] Parallel.

were maximum launch acceleration and top vehicle speed. Each of these concepts met those requirements, so the comparison of fuel economy and 0–60 mph acceleration time reported here can now be made on an “equal-performance” basis.

The **Tank-to-Wheel Efficiency** (column 6 in Table ES-2.1) is a measure of the overall efficiency of the vehicle system, defined as:

$$Tank\ to\ Wheels\ Eff = \frac{Energy\ Output}{Energy\ Input}$$

where the energy output of the drive system is the total amount of energy required to overcome the rolling resistance, aerodynamic, and inertial (acceleration) load over the driving cycle:

$$Energy\ Output = \sum \left[\left(Roll\ Resist \right) + \left(Aero\ Resist \right) + \left(Ma \right) \right] * V * \Delta t = Energy @ Wheels$$

and the total amount of energy input to the system is defined as:

$$Energy\ Input = Energy\ Value\ of\ Fuel\ Consumed$$

The vehicle fuel economy (on a gasoline-equivalent basis) and expected emission levels are summarized in Table ES-2.2. The fuel economy from Table ES-2.1 is shown here as the "50" entry — meaning that there is a 50% likelihood that the fuel economy may be higher (because of presently unexpected technological advances) or lower (because of unforeseen difficulties). The columns labeled 20 and 80 denote estimates for which the fuel economy has only a 20% likelihood of being below the lower bound and a 20% likelihood of being above the upper bound, respectively.

Table ES-2.2 Overview of Vehicle Configurations

		Fuel Economy (mpg GE)			
No.	Vehicle Configuration	20 percentile[a]	50 percentile[b]	80 percentile[c]	Emission Standard[d]
1	Gasoline CONV SI (baseline)	19.2	20.2	26.3	Tier 2 Bin 5
2	Diesel CONV CIDI	22.0	23.8	30.9	"
3	E85 CONV SI	19.2	20.2	26.3	"
4	CNG CONV SI	18.8	19.8	25.7	"
5	Gasoline SI HEV[e, f]	22.2	24.4	30.5	"
6	Diesel CIDI HEV[f]	26.7	29.4	36.8	"
7	E85 SI HEV[f]	22.2	24.4	30.5	"
8	Gasoline FP FCV	23.7	27.2	32.6	Tier 2 Bin 2
9	Gasoline FP FC HEV	26.2	30.2	36.2	"
10	Methanol FP FCV	26.3	30.3	36.4	"
11	Methanol FP FC HEV	30.0	34.5	41.4	"
12	Ethanol FP FCV	24.9	28.6	34.3	"
13	Ethanol FP FC HEV	27.6	31.8	38.2	"
14	G.H_2 FCV/L.H_2 FCV	39.3	43.2	47.5	Tier 2 Bin 1
15	G.H_2 FC HEV/L.H_2 FC HEV	43.7	48.1	52.9	"

[a] 20% likelihood mpg lower.
[b] Equally likely above or below.
[c] 20% likelihood mpg higher.
[d] Federal standards: Tier 2 Bin 5, Tier 2 Bin 2 (SULEV II), Tier 2 Bin 1 (ZEV).
[e] All HEVs are charge sustaining.
[f] Parallel.

ES-2.4 Conclusions

On the basis of the results listed in Table ES-2.1, GM made the following observations:

- FC systems use less energy than conventional powertrains because of the intrinsically higher efficiency of the FC stack.
- Hybrid systems show consistently higher fuel economy than conventional vehicles because of regenerative braking and engine-off during idle and coast periods (thus, the improvements occur mostly on the urban driving schedule).
- In the case of the FC and FP systems, the gains resulting from hybridization are lower because the "engine-off" mode is present in both systems.

- Hydrogen-based FC vehicles exhibit significantly higher fuel economy than those that employ a FP.

Again, important factors such as packaging, cold start, transient response, and cost were not considered within the scope of this work. This portion of the study addresses TTW efficiencies; when combined with the WTT analysis, it will provide the full-cycle WTW efficiencies.

PART 3

Well-to-Wheel Fuel/Vehicle Pathway Integration

ES-3.1 Introduction

Part 1 of this report presented energy use and greenhouse gas (GHG) emissions on a well-to-tank (WTT) basis for 75 fuel pathways analyzed by Argonne National Laboratory. In many cases, Argonne found that the results for various pathways were so similar that it was possible to reduce the number of the pathways by selecting a "representative" fuel within a fuel category. This was true for multiple gasoline and diesel pathways. Argonne pared its results down to 30 representative fuel pathways. For Part 2, researchers from GM quantified the energy use of 15 advanced powertrain systems (tank-to-wheel [TTW] analysis) (see Table ES-2.2).

This part of the report combines the results of Parts 1 and 2 into an analysis of well-to-wheel (WTW) efficiency and GHG emissions — providing a complete view of these alternative fuel/vehicle pathways. The first part of the Methodology section (Part A) describes the process and criteria used to reduce the 30 representative pathways selected in Part 1 to 13 pathways. The second part of the Methodology section (Part B) describes the process used to combine these 13 fuel pathways with the 15 vehicle pathways identified in Part 2 to obtain 27 fuel/vehicle combinations for further analysis of their WTW energy use and GHG emissions characteristics.

ES-3.2 Methodology

Part A: Selection of Well-to-Tank Pathways

In addition to the 30 fuel pathways identified in the WTT portion of the study, two E85 pathways were added to facilitate analysis of the two E85-fueled vehicles analyzed in Part 2 (see Table ES-2.2). Fuel use and GHG emissions information for the two E85 pathways (corn and herbaceous) is contained in Appendix B in Volume 3 of this report series. The 32 pathways were reduced to 13 on the basis of two criteria: resource availability and energy use. Two other criteria that can be used for screening fuel/technology pathways — economic/investment issues and technological hurdles — were not considered in this study, but may be addressed in follow-on work. The two electricity fuel pathways were not considered because neither battery-powered electric vehicles nor charge-depleting hybrid electric vehicles (HEVs) were considered (for reasons outlined in Part 2).

Resource Availability

During the integration analysis, we excluded 12 of the 30 fuel pathways selected in Part 1 on the basis of resource availability — the pathways involving North American natural gas (NG) (eight NG- and two electrolysis-based) and corn-based ethanol.

North American NG-Based Pathways. The current and potential North American NG resource base appears to be insufficient to supply wide-scale use of NG for transportation fuels in the U.S. market. Three recent studies cited in our report suggest that rapid incremental NG demand in the

United States, in particular for electricity generation, will put pressure on the North American gas supply, even without a significant transportation demand component. In order to supply a significant share of the transportation fuel market, NG would have to be obtained overseas eventually, primarily from Russia, Iran, and other Middle East nations.

Consistent with these studies, our assessment of NG resources is that high-volume, NG-based, light-duty fuel pathways would have to rely on non-North-American NG; as a result, we considered examination of non-North-American NG-based pathways to be far more feasible than North American NG-based pathways and dropped the latter from our analysis.

Corn Ethanol-Based Pathways. The current use of ethanol as a transportation fuel in the United States is about 1.5 billion gallons per year — equivalent to about 1 billion gallons of gasoline (on an energy basis). Today, the United States consumes in excess of 100 billion gallons of gasoline per year.

Recent U.S. Department of Agriculture (USDA) simulations show that production of corn-based ethanol could be doubled — to about 3 billion gallons per year — without drastic impacts on the animal feed and food markets.

Although the production of corn ethanol could be doubled in ten years, the amount produced still would be adequate to supply only the ethanol blend market. It does not appear that the supply of corn-based ethanol will be adequate for use in high-volume transportation applications; as a result, we eliminated corn-based ethanol from the analysis.

The economics of cellulosic ethanol are not currently competitive with those of gasoline. Further, it has yet to be determined whether cellulosic biomass faces resource availability constraints. Also, some experts have concluded that the technology for producing biofuels will have to be significantly improved to make this pathway viable. Because of the uncertainty here, we carried this pathway along to the WTW analysis.

Energy Efficiency

We eliminated two fuel pathways on the basis of energy inefficiency. NG-based liquid hydrogen (L.H_2) produced at stations is significantly less efficient than L.H_2 produced at central plants. The low end of the distribution of efficiency estimates for L.H_2 produced at central plants is higher than the highest value of the distribution for L.H_2 produced at refueling stations — there is no overlap in the percentile range. Because the two candidate fuels are used in the same fuel cell vehicle (FCV), we eliminated the less efficient of the pair, L.H_2 produced at stations.

All four electrolysis pathways presented in Part 1 would normally be excluded because they do not offer acceptable energy efficiency and GHG emissions characteristics. The WTW efficiencies for several competing NG-based vehicles are already higher than the efficiencies in the electrolysis pathways based solely upon the WTT stage (Part 1 of the study). Many proponents of electrolysis, however, point to its potential use in the transition to high-volume H_2 FCV applications. For this reason, we exclude only the less efficient of the electrolysis pathways, L.H_2.

Fischer-Tropsch (FT) naphtha, a candidate reformer fuel for FCVs, is surpassed by crude naphtha on a WTT efficiency basis because both candidate fuels can be used in the same vehicle. Likewise, Fischer-Tropsch diesel (FTD) offers lower energy efficiency than crude-based diesel. However, because the FT fuels are of interest to a broad range of analysts and may have other benefits (e.g., criteria pollutants) not captured in this analysis, they have not been eliminated from consideration.

Predicated on the screening logic described above, we pared the number of fuel pathways considered to the 13 listed in Table ES-3.1. These fuels, taken together with the 15 vehicles considered in Part 2, yield the 27 fuel/vehicle pathways analyzed on a WTW basis in this study.

Table ES-3.1 Summary of Pathways Selected for WTW Integration Analysis

	Pathways	Excluded		Carried to Well-to-Wheel Analysis	No.
		Resource Availability	Energy Efficiency		
	Pathways Identified in Part 1				
	Oil-Based				
1	Current gasoline	Used as reference only.			
2	Low-sulfur gasoline			X	1
3	Current diesel	Used as reference only.			
4	Low-sulfur diesel			X	2
5	Crude naphtha			X	3
	Natural-Gas-Based				
6	CNG: NA NG	X			
7	CNG: NNA NG			X	4
8	MeOH: NA NG	X			
9	MeOH: NNA NG			X	5
10	FT naphtha: NA NG	X			
11	FT naphtha: NNA NG			X	6
12	FTD: NA NG	X			
13	FTD: NNA NG			X	7
14	G.H_2 – central plants: NA NG	X			
15	G.H_2 – central plants: NNA NG			X	8
16	L.H_2 – central plants: NA NG	X			
17	L.H_2 – central plants: NNA NG			X	9
18	G.H_2 – stations: NA NG	X			
19	G.H_2 – stations: NNA NG			X	10
20	L.H_2 – stations: NA NG	X			
21	L.H_2 – stations: NNA NG		X		
	Electricity-Based				
22	Electricity: U.S. mix				
23	Electricity: CC turbine, NA NG	Discussed in Part 2			
	Electrolysis-Based				
24	G.H_2 electrolysis: U.S. mix			X	11
25	G.H_2 electrolysis: CC turbine, NA NG	X			
26	L.H_2 electrolysis: U.S. mix		X		
27	L.H_2 electrolysis: CC turbine, NA NG	X			
	Ethanol-Based				
28	E100: corn	X			
29	E100: herbaceous cellulose			X	12
30	E100: woody cellulose[a]				
	Additional Pathways Considered				
31	E85: corn	X			
32	E85: herbaceous cellulose			X	13

[a] Deleted: herbaceous cellulose considered representative of cellulosic pathways.

Part B: Well-to-Wheel Integration

The GM WTW integration modeling process takes stochastic outputs from Parts 1 and 2 for efficiency and GHG emissions and combines them into complete WTW results (see Figure ES-3.1).

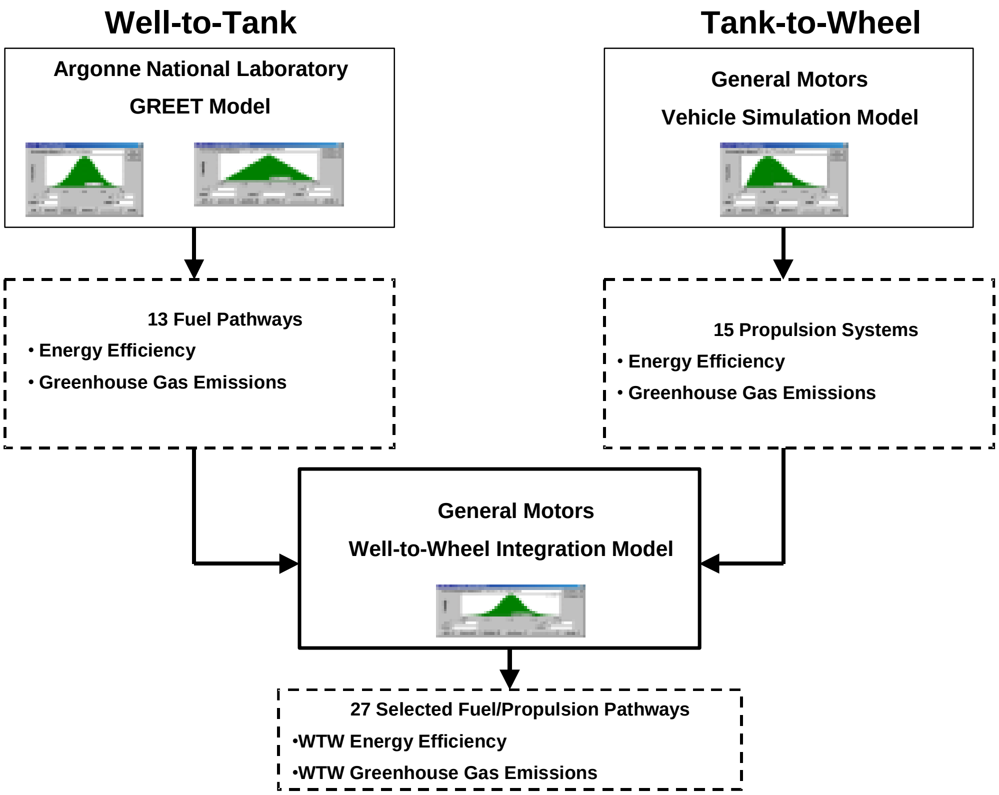

Figure ES-3.1 WTW Integration Process

Well-to-Tank (Part 1)

The GREET model results for the WTT energy use are presented as a probability distribution for energy use and GHG emissions for each fuel pathway. For the integration analysis, these results were fitted to a set of continuous distributions using well-known goodness-of-fit tests. For each of the resulting 26 distributions (energy use and GHG emission for 13 fuels), the logistic distribution was the best-fitting distribution.

Tank-to-Wheel (Part 2)

Part 2 of this study provides 20, 50, and 80 percentile fuel use estimates (in mpg gasoline equivalent) for 15 fuel/vehicle configurations (see Table ES-2.2). During the WTW integration process, each of these 20-50-80 percentiles was used to fit a Weibull distribution to each of the 15 fuel/vehicle configurations.

The CO_2 component of the GHGs contributed by the vehicle are related to the carbon content of the fuel because it is all combusted in the vehicle. Of course, there is no carbon in hydrogen fuels, so there is no CO_2 contribution from FCVs powered by H_2. GHGs other than CO_2 were considered negligible at the vehicle level for the other fuel/vehicle pathways.

Well-to-Wheel (Part 3)

The WTT total energy use per mile for each fuel was computed on the basis of information provided in Part 1; vehicle fuel use per mile was computed from data provided in Part 2. Once the distributions from Parts 1 and 2 were developed, the joint probability distributions for WTW energy use and GHG emissions were simulated by using the Monte Carlo method. For example, 20, 50, and 80 percentiles for both energy use and GHG emissions are shown in the figures in Section ES-3.3. The end points of the bars in the figures are the 80 and 20 percentile points: the 50 percentile points of the various pathways are indicated by diamonds.

ES-3.3 Results

The analysis that follows addresses the 27 fuel/vehicle pathways listed in Table ES-3.2 in terms of their total system energy use (in Btu/mi) and GHG emissions (in g/mi). Spark-ignition (SI) and compression-ignition direct-injection (CIDI) conventional and hybrid fuel/vehicle pathways are evaluated first, followed by HEV fuel cell vehicles, and non-hybridized FCVs. This section ends with a comparison of those pathways that appear to offer superior performance on the basis of energy use (Btu/mi) and GHG emissions (g/mi). It is very important to note that other factors (e.g., criteria pollutants, incremental fuel and vehicle costs) were not considered as part of our study.

Conventional and Hybrid Fuel/Vehicle Pathways

Figure ES-3.2 shows the total system energy use (in Btu/mi) for conventional and hybrid fuel/vehicle pathways powered by SI or CIDI engines.

The figure shows that:

- The diesel CIDI HEV uses the least amount of total energy.
- The diesel CIDI conventional vehicle and the gasoline SI HEV yield roughly the same total system energy use.
- The CNG SI conventional vehicles offer no energy use benefit over gasoline conventional vehicles.
- FTD, even in a comparable technology vehicle (CONV or HEV), is more energy-intensive than crude-based diesel.
- There is considerable opportunity for energy use improvement over the 50 percentile estimates for all pathways, including the baseline gasoline SI conventional vehicle.
- Hybridizing these vehicles reduces energy use by over 15% (see Volume 2, Part 3B).

Table ES-3.2 Fuel/Vehicle Pathways Analyzed

No.	Fuel Pathway	Vehicle Configuration	Fuel Abbreviation	Vehicle Abbreviation
1	Low-sulfur gasoline	Gasoline CONV SI	GASO	SI CONV
2	Low-sulfur diesel	Diesel CONV CIDI	DIESEL	CIDI CONV
3	FTD: NNA NG	Diesel CONV CIDI	FTD	CIDI CONV
4	E85: herbaceous cellulose	E85 CONV SI	HE85	SI CONV
5	CNG: NNA NG	CNG CONV SI	CNG	SI CONV
6	Low-sulfur gasoline	Gasoline SI HEV[a,b]	GASO	SI HEV
7	Low-sulfur diesel	Diesel CIDI HEV[b]	DIESEL	CIDI HEV
8	FTD: NNA NG	Diesel CIDI HEV[b]	FTD	CIDI HEV
9	E85: herbaceous cellulose	E85 SI HEV[b]	HE85	SI HEV
10	Low-sulfur gasoline	Gasoline FP FCV	GASO	FP FCV
11	Crude naphtha	Gasoline FP FCV	NAP	FP FCV
12	FT naphtha: NNA NG	Gasoline FP FCV	FT NAP	FP FCV
13	Low-sulfur gasoline	Gasoline FP FC HEV	GASO	FP FC HEV
14	Crude naphtha	Gasoline FP FC HEV	NAP	FP FC HEV
15	FT naphtha: NNA NG	Gasoline FP FC HEV	FT NAP	FP FC HEV
16	MeOH: NNA NG	Methanol FP FCV	MEOH	FP FCV
17	MeOH: NNA NG	Methanol FP FC HEV	MEOH	FP FC HEV
18	E100: herbaceous cellulose	Ethanol FP FCV	HE100	FP FCV
19	E100: herbaceous cellulose	Ethanol FP FC HEV	HE100	FP FC HEV
20	G.H_2 – stations: NNA NG	G.H_2 FCV	G.H_2 RS	FCV
21	G.H_2 – stations: NNA NG	G.H_2 FC HEV	G.H_2 RS	FC HEV
22	G.H_2 – central plants: NNA NG	G.H_2 FCV	G.H_2 CP	FCV
23	G.H_2 – central plants: NNA NG	G.H_2 FC HEV	G.H_2 CP	FC HEV
24	L.H_2 – central plants: NNA NG	L.H_2 FCV	L.H_2	FCV
25	L.H_2 – central plants: NNA NG	L.H_2 FC HEV	L.H_2	FC HEV
26	G.H_2 electrolysis: U.S. mix	G.H_2 FCV	G.H_2 EL	FCV
27	G.H_2 electrolysis: U.S. mix	G.H_2 FC HEV	G.H_2 EL	FC HEV

[a] All HEVs are charge sustaining.
[b] Parallel.

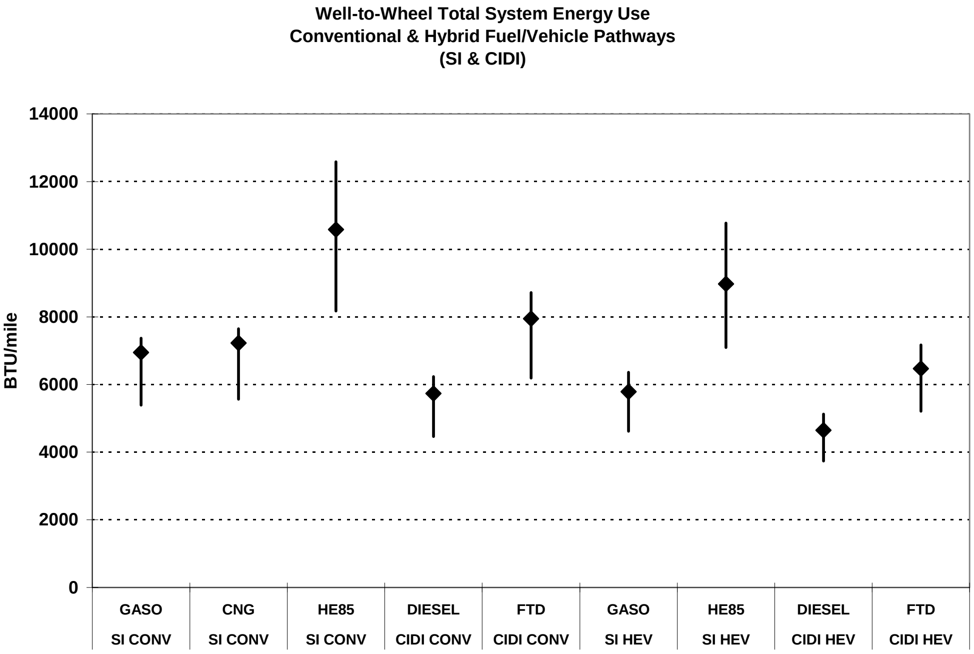

Figure ES-3.2 WTW Total System Energy Use: Conventional and Hybrid Fuel/Vehicle Pathways (SI and CIDI)

From the standpoint of GHG emissions, as shown in Figure ES-3.3:

- The herbaceous E85 (HE85)-fueled vehicles have by far the lowest GHG emissions.
- Among the other vehicles, the diesel CIDI HEV yields the largest potential GHG benefit.
- The CNG SI conventional vehicle generates somewhat higher GHG emissions than the diesel CIDI conventional vehicle.
- The FTD CIDI conventional vehicle and HEV have slightly higher GHG emissions than the crude oil-based diesel CIDI conventional vehicle and HEV.
- Once again, the asymmetric distributions indicate considerable opportunity for new-technology-based improvements in GHG emissions for all vehicles.

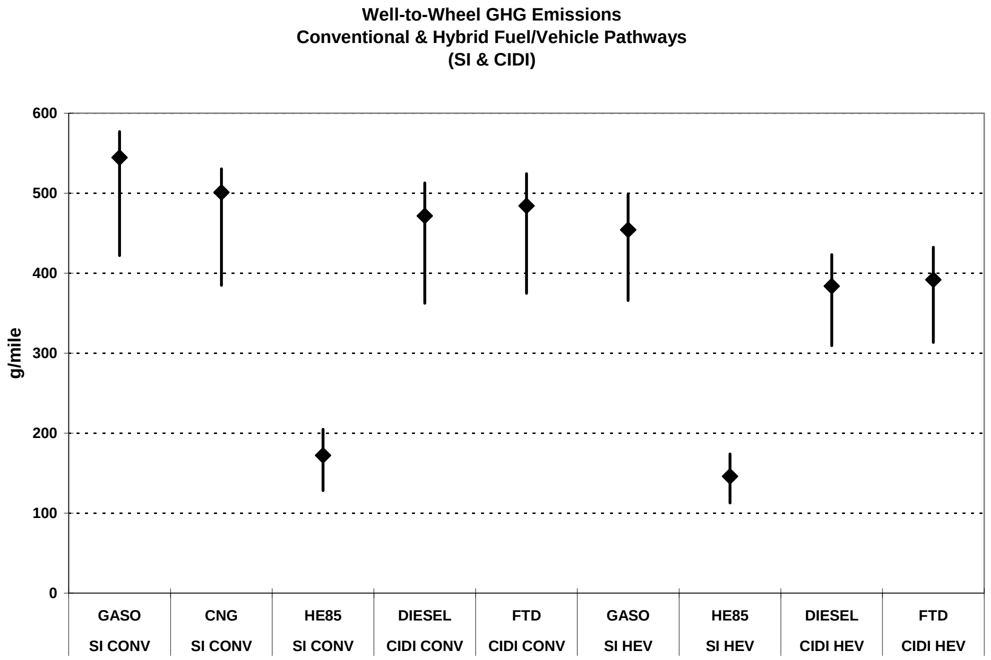

Figure ES-3.3 WTW GHG Emissions: Conventional and Hybrid Fuel/Vehicle Pathways (SI and CIDI)

Fuel/Hybrid and Non-Hybrid FCV Pathways

Nine different fuel/FCV combinations were analyzed in terms of their total system energy use and GHG emissions performance. Because the hybrid versions of these FCVs show an approximately 10% advantage (see Volume 2, Part 3B) over their non-hybrid counterparts in terms of total systems energy use, their analysis results are discussed here.

As illustrated in Figure ES-3.4:

- Gasoline and naphtha fuel processor-based FC HEVs, as well as H_2-fueled FC HEVs for which the H_2 is produced centrally or at the retail site from non-North-American NG, all offer the best total system energy use.

- Hybridized FCVs fueled by L.H_2 and FT naphtha involve higher energy consumption; MeOH use results in higher energy consumption, but is not statistically[2] different from gasoline, crude naphtha, or G.H_2.

- The electrolysis-based H_2 FC HEV uses significantly more energy than the other pathways.

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[2] Considering two pathways, if the 50-percentile (P_{50}) point of one pathway lies outside the 20–80 percentile (P_{20}–P_{80}) range of a second pathway, the P_{50} points of the two pathways are deemed to be statistically different.

- The HE100-based pathway fares poorly on total system energy use, although a significant portion of the energy used is renewable.

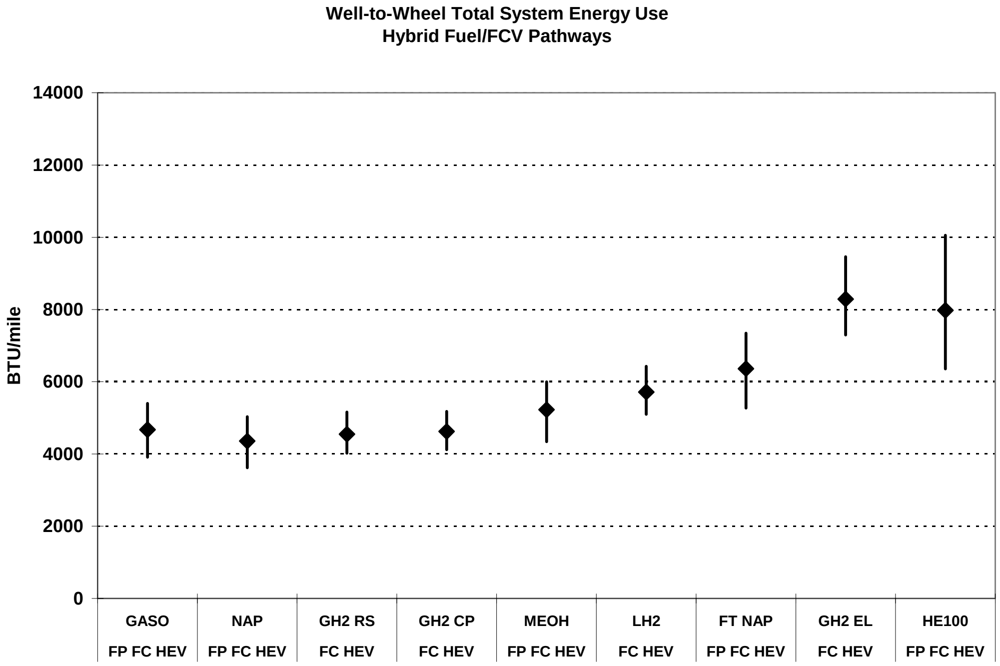

Figure ES-3.4 WTW Total System Energy Use: Hybrid Fuel/FCV Pathways

As shown in Figure ES-3.5, from a GHG standpoint, the analysis suggests:

- As expected, the HE100 FP FC HEV emits by far the lowest amount of GHGs.
- GHG emissions from the next lowest emitters, the two H_2 FC HEVs, are statistically the same.
- The naphtha and methanol FP FC HEVs are basically tied for third place.
- Gasoline FP FC HEVs and L.H_2 FC HEVs are statistically tied for fourth place.
- The G.H_2 electrolysis FC HEV pathways have the highest GHG emissions.

Figures ES-3.6 and ES-3.7 show non-hybridized versions of the pathways shown in Figures ES-3.4 and ES-3.5. In all cases, the energy use and GHG emissions are higher than for the corresponding hybridized FCVs. A quick review reveals that all of the rank order findings discussed above for the hybrid FCVs also apply to non-HEV versions.

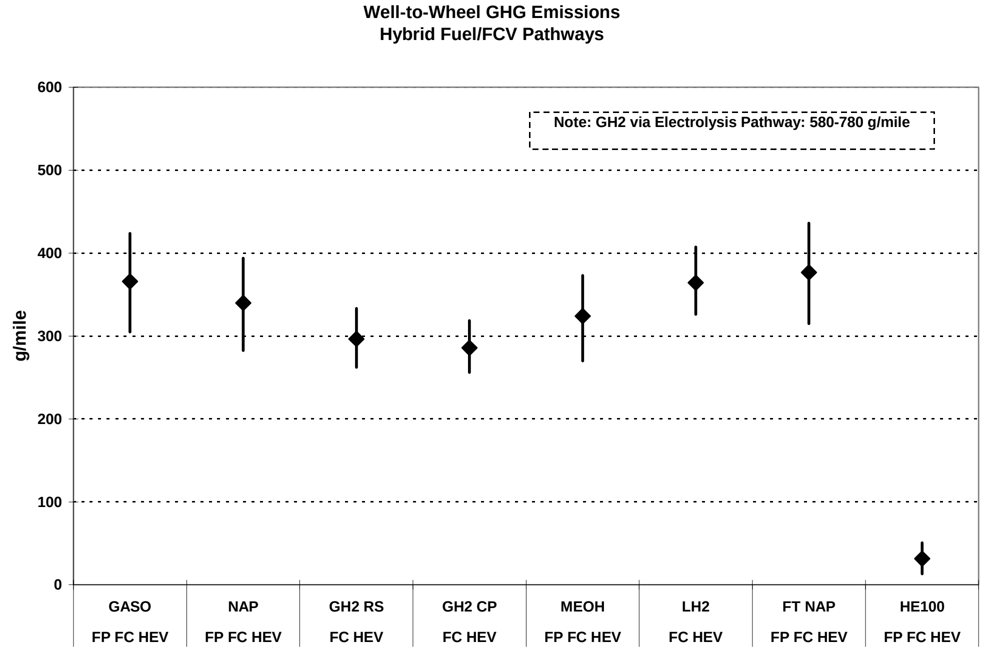

Figure ES-3.5 WTW GHG Emissions: Hybrid Fuel/FCV Pathways

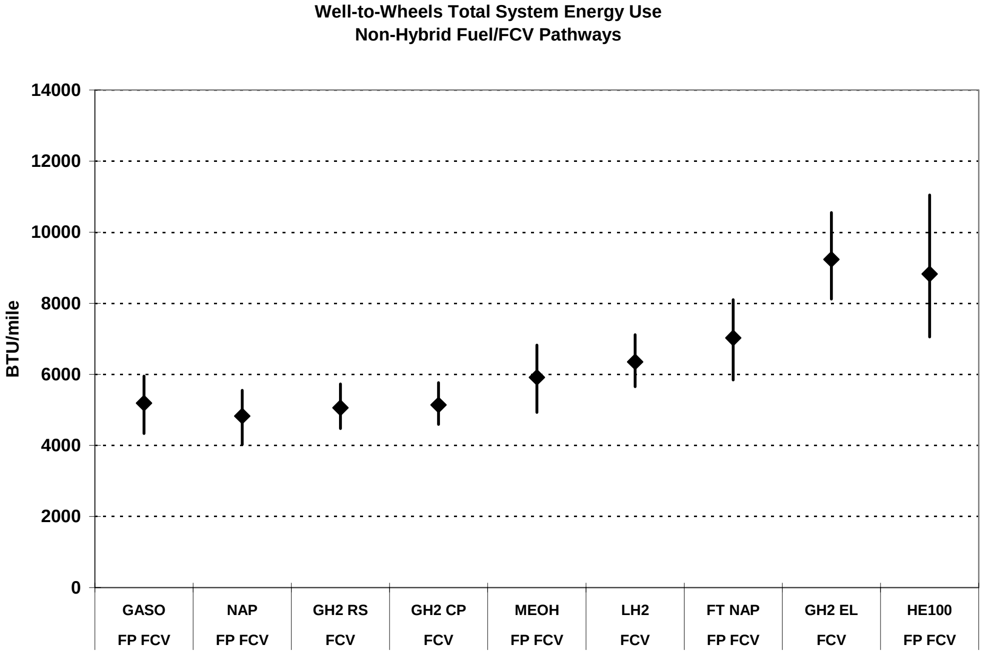

Figure ES-3.6 WTW Total System Energy Use: Non-Hybrid Fuel/FCV Pathways

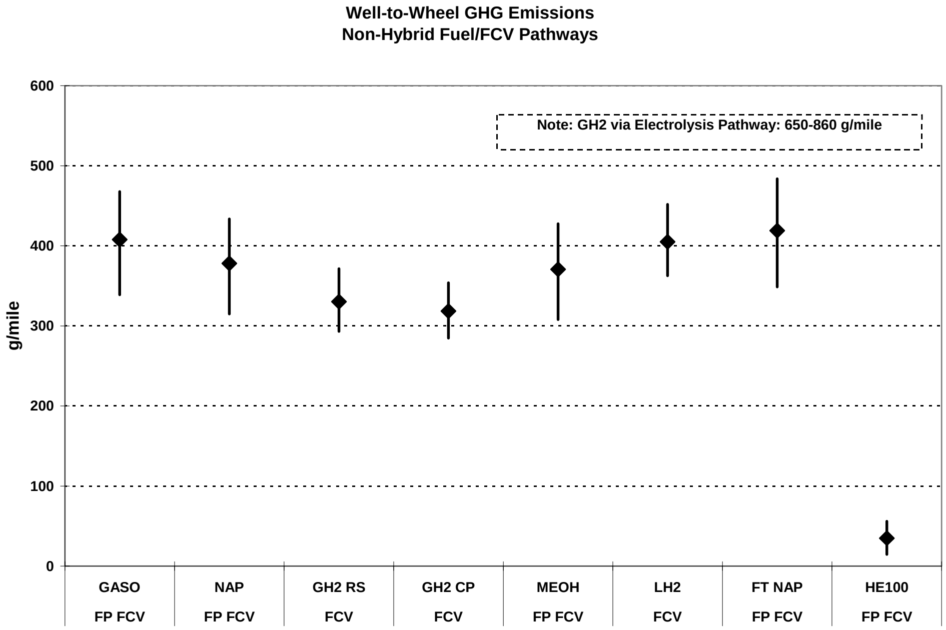

Figure ES-3.7 WTW GHG Emissions: Non-Hybrid Fuel/FCV Pathways

ES-3.4 Conclusions

Fuel Use

Key findings include the following:

- Figure ES-3.8 summarizes our results for total system energy use for selected pathways. From a statistical standpoint, the diesel CIDI HEV, gasoline and naphtha FP FC HEVs, as well as the two H_2 FC HEVs (represented by the G.H_2 [refueling station] FC HEV only in the figures) are all the lowest energy-consuming pathways.

- Figure ES-3.9 illustrates an interesting finding: all of the crude oil-based selected pathways have WTT energy loss shares of roughly 25% or less. The H_2 FC HEV share is over 60%; the MeOH FP FC HEV share is about 50%. A significant fraction of the WTT energy use of ethanol is renewable — over 90% for HE100.

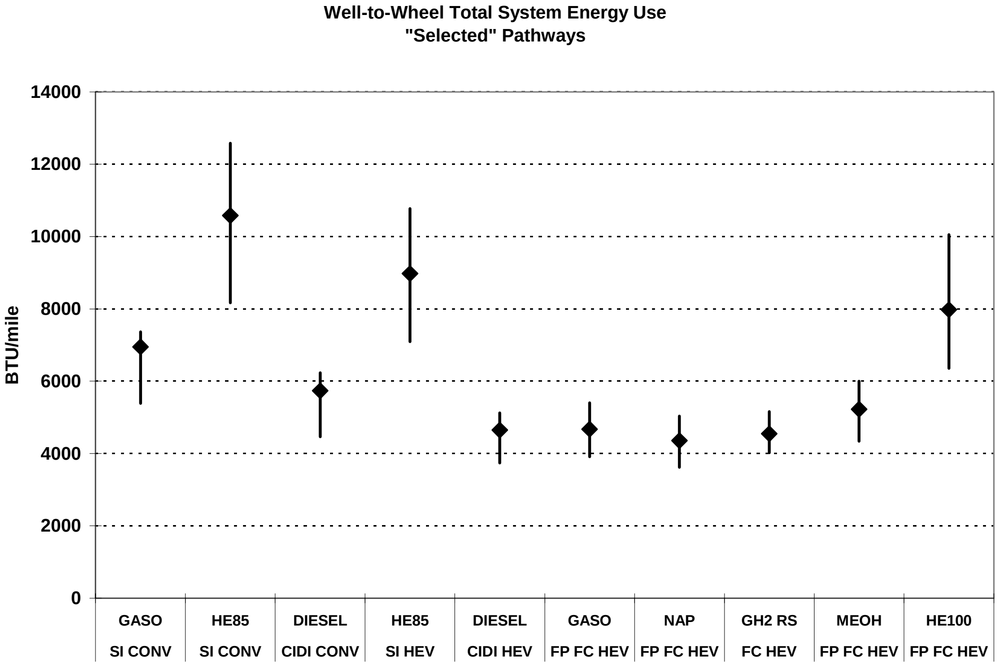

Figure ES-3.8 WTW Total System Energy Use: "Selected" Fuel/Vehicle Pathways

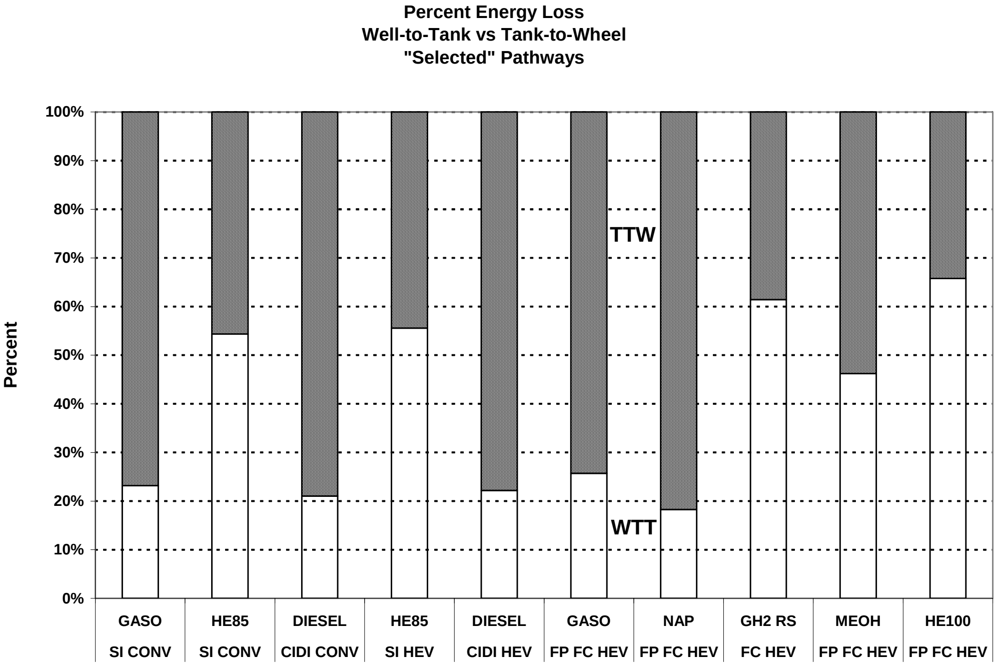

Figure ES-3.9 Percent Energy Loss WTT vs. TTW: "Selected" Fuel/Vehicle Pathways

Greenhouse Gas Emissions

Key GHG findings are summarized in Figure ES-3.10 and include the following:

- The ethanol-fueled vehicles, as expected, yield the lowest GHG emissions per mile.
- The next lowest are the two H_2 FC HEVs (represented by the G.H_2 [refueling station] FC HEV in the figure).
- The H_2 FC HEVs are followed by the MeOH, naphtha, and gasoline FP HEVs and the diesel CIDI HEV, in that order.
- The diesel CIDI HEV offers a significant reduction in GHG emissions (27%) relative to the gasoline conventional SI vehicle.

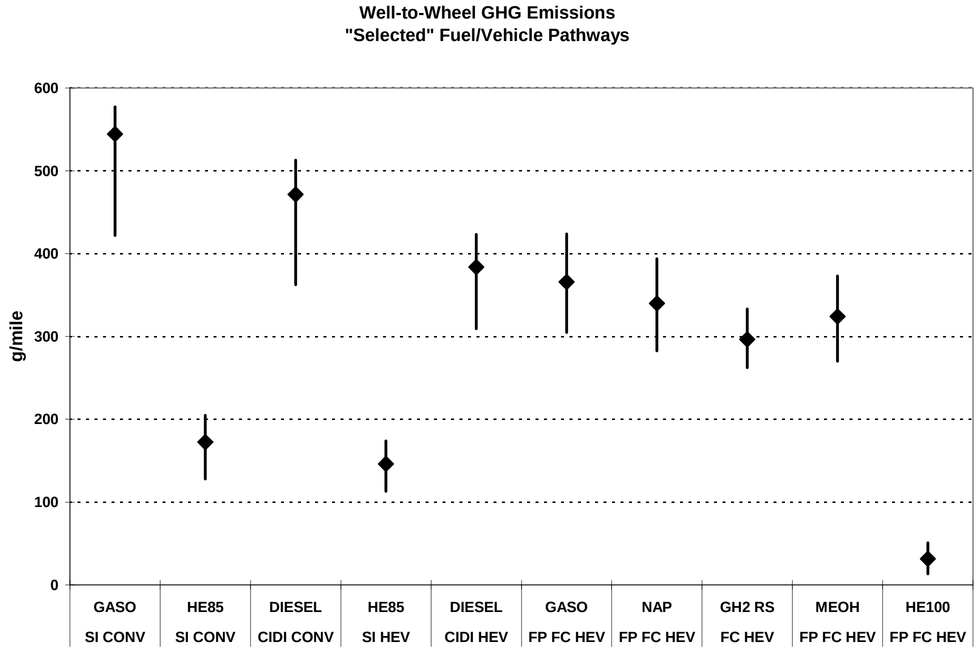

Figure ES-3.10 WTW GHG Emissions: “Selected” Fuel/Vehicle Pathways

Integrated Fuel Use/GHG Emissions Results

Considering both total energy use and GHG emissions, the key findings are as follows:

- Among all of the crude oil- and NG-based pathways studied, the diesel CIDI HEV, gasoline and naphtha FP FC HEVs, and G.H_2 FC HEVs, were nearly identical and best in terms of total system energy use (Btu/mi). Among these pathways, however, expected GHG emissions were lowest for the H_2 FC HEV and highest for the diesel CIDI HEV.

- Compared to the gasoline SI (conventional), the gasoline SI and diesel CIDI HEVs, as well as the diesel CIDI (conventional) yield significant total system energy use and GHG emission benefits.

- The MeOH FP FC HEV offers no significant energy use or emissions reduction advantages over the crude oil-based or other NG-based FC HEV pathways.

- Ethanol-based fuel/vehicle pathways have by far the lowest GHG emissions of the pathways studied and also do very well on WTT energy loss when only fossil fuel consumption is considered.

- It must be noted that for the HE100 FP FC HEV pathway to reach commercialization, major technology breakthroughs are required for both the fuel and the vehicle.

- On a total system basis, the energy use (Btu/mi) and GHG emissions of CNG conventional and gasoline SI conventional pathways are nearly identical.

- The crude oil-based diesel vehicle pathways offer slightly lower total system GHG emissions and considerably better total system energy use than the NG-based FTD CIDI vehicle pathways. (Note that criteria pollutants are not considered here.)

- L.H_2, FT naphtha, and electrolysis-based H_2 FC HEVs have significantly higher total system energy use and the same or higher levels of GHG emissions than the gasoline and crude naphtha FP FC HEVs and the G.H_2 FC HEVs.